Sensor & Platform Technology Requirements for Implementing NASA's Earth Science Research Strategy in the Next Decade:

A Summary Report Based on the ESTO Technology Planning Workshop Held on March 5-6, 2003

ESTO

This summary report is based on the results of the ESTO Technology Planning Workshop held in Pasadena, California, on March 5-6, 2003. A list of workshop executive panel members and workshop participants appears in appendices A and B, respectively.

This summary report is authored by: Azita Valinia (NASA/ESTO), Jon Neff (Aerospace), Robert Kinsey (Aerospace), and David Tratt (NASA/ESTO). The authors are grateful for many valuable discussions with the executive panel members toward preparing this summary report. The authors particularly thank Loren Lemmerman (JPL) and Mahta Moghaddam (JPL) for their extensive comments, suggestions, and contributions toward this summary.

The detailed technology requirements discussed and validated by workshop participants (and on which this summary report is based) are available in searchable format from the Earth Science Technology Integrated Planning System (ESTIPS) database at

http://esto.nasa.gov/estips/

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1. Introduction

1.1 Workshop Purpose

Implementing NASA's Earth Science Enterprise (ESE) research strategy for the next decade requires state of the art remote sensing and in situ observational technologies. In order to define future technology requirements and plan for the development and acquisition of such needed technologies, NASA's Earth Science Technology Office (ESTO) sponsored a public technology planning workshop at the Hilton Hotel in Pasadena, CA, on March 5-6, 2003. Workshop participation was open to U. S. industry, academia, federally funded research and development centers, and U.S. government organizations.

The workshop participants were charged to:

- Identify and quantify sensor and platform technology capabilities needed to implement Earth Science Research Strategy in the next decade
- Map the technology requirements to the future scientific measurements that will be enabled
- Categorize identified technology requirements as either *enabling* or *enhancing*

1.2 Workshop Process

The workshop was organized into five parallel panels in focused technology areas. These were:

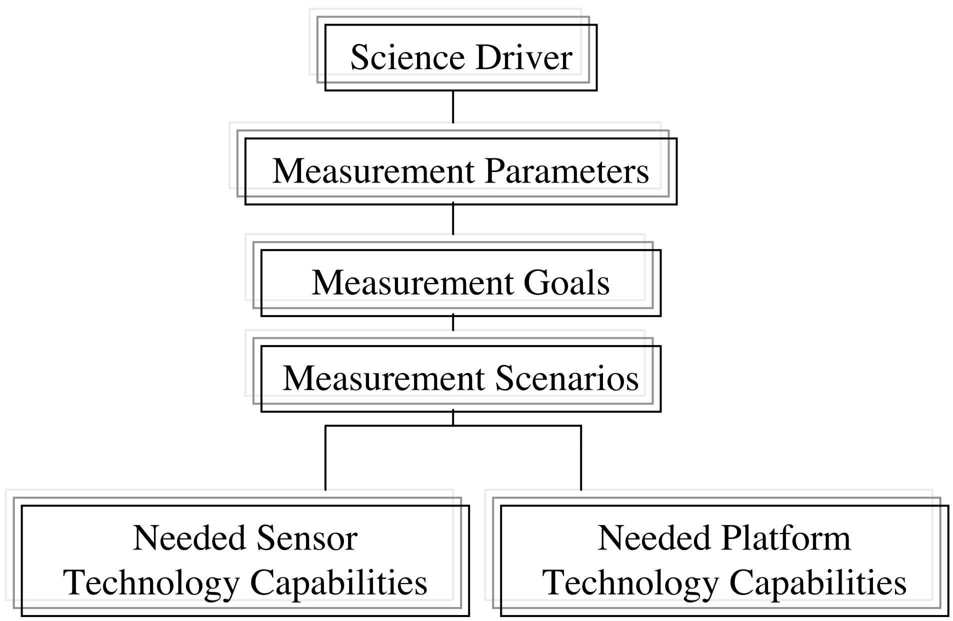
- Active Remote Sensing I: Laser/Lidar technologies
- Active Remote Sensing II: Radar technologies
- Passive Remote Sensing I: UV/optical/IR technologies
- Passive Remote Sensing II: Microwave and radio frequency technologies
- In-situ sensing, unconventional or non-spaceborne technologies (e.g. quantum gravity gradiometer, bistatic radar, GPS as a science instrument, etc.); and platform technologies

The workshop began with a plenary session. Mr. George Komar, Earth science technology program manager, welcomed the participants and gave them an overview of the technology program conducted at the Earth Science Technology Office (ESTO). Dr. Jack Kaye, director of the research division at ESE, NASA/HQ, gave an overview of NASA's Earth science research priorities and roadmaps. Afterwards, Dr. Azita Valinia, technology planning manager at ESTO, gave an overview of the technology planning process and defined the scope, objectives, approach, and products expected from the workshop. The workshop was then reconvened into the five breakout sessions.

Prior to the workshop, the ESTO planning team had identified a set of measurement scenarios and corresponding technology requirements for implementing the ESE research strategy. These requirements were reviewed by more than 100 scientists and technologist at NASA centers and reviewer feedback was captured in the set of requirements. Each breakout session began with the set of reviewed measurement scenarios and corresponding technology requirements. At the workshop, participants were asked to validate and finalize the technology requirements for implementing NASA's ESE research strategy in the next decade. The workshop concluded with a plenary summary session at the end of the second day.

2. Science Drivers and Technology Options

Prior to the workshop, ESE program scientists at NASA Headquarters provided a top level set of science requirements based on ESE research strategy for 2000-2010. Based on these science drivers, the ESTO planning team drafted a set of technology options and corresponding capability needs for each of the science requirements. Each technology option represents a measurement scenario for a particular measurement parameter (e.g. ice surface topography) using a particular technology approach (e.g. laser altimetry or radar altimetry) from a specified measurement platform (airborne or spaceborne). The science to technology requirements flow down is as follows:



In what follows, we describe the science to technology requirement flow down for each of the ESE science themes. In addition to observational technologies, fulfilling the science goals of the climate and weather theme requires robust computational technologies. Since this workshop covered only sensor and platform technologies, the discussion of needed computational capabilities is beyond the scope of this report. We refer the reader to the report from the ESE Computational Technology Requirements Workshop 2002 (sponsored by ESTO).

2.1 Atmospheric Composition

Table 1 shows a summary of science requirements in the atmospheric composition theme provided by the cognizant ESE program scientists at NASA HQ.

Based on the science requirements presented in Table 1, a total of 51 measurement scenarios were discussed and validated at the workshop. These detailed scenarios and their corresponding technology requirements can be found in ESTIPS by searching the "Science Drivers" -> "Atmospheric Composition" theme. A summary of the technology options and corresponding required capabilities to meet the requirements for this theme appears in Table 2.

The majority of measurements in this theme are performed via active optical remote sensing techniques such as the use of lidar technologies on either spaceborne or airborne platforms, or passive techniques such as spectrometry, radiometry, and imaging in the UV, optical, and IR band, or sounding techniques in the microwave band.

Atmospheric Properties & Ozone There are a variety of scenarios for the measurement of ozone and precursors. One scenario for measurement of vertical profiles of atmospheric constituents, ozone and precursors is the use of microwave sounding technique from LEO. In an atmospheric occultation, a signal transmitted by a LEO satellite is received by another forming a rising or setting pair through the Earth's atmosphere thereby providing vertical profiles of various atmospheric constituents. Ability for onboard processing of huge volume of data, navigation and pointing accuracy, as well as antenna systems capable of fast scanning the Earth's limb are needed for this scenario.

Atmospheric properties in the tropopause can also be measured via observing thermal emission from the atmospheric limb. Antenna systems capable of fast scanning Earth's limb, and long lifetime space qualified cryocoolers are needed for this scenario.

Height resolved measurements of tropospheric ozone can be achieved by using a UV DIAL in a highly inclined low Earth orbit to provide coverage of the mid-latitudes. Deployable, 3-6 m class telescopes, and high power, compact UV laser to penetrate the ozone layer are among the requirements for this scenario.

The use of a variety of broadband spectrometers (based on the heritage of SAGE) from polar LEO or mounted on ISS is another option. The sensor scans the limb of the Earth during sunrise/sunset and measures solar transmission through the atmosphere. Lunar or stellar occultations may also be observed. High performance cooled detectors, accurate and stable onboard calibration, and DSP chip speed increase by an order of magnitude over the current state of art are some of the requirements.

Another approach is the use of a multi waveband imaging spectrometer from LEO or GEO based on the heritage of TOMS. Rad-hard CCD or CCD hybrid detectors with high SNR, and advanced onboard lossless data compression are needed for this scenario.

A solid state linear variable etalon IR spectrometer for long term monitoring of altitude profiles of stratospheric/upper tropospheric ozone, and various nitrogen and chlorine sources at high vertical resolution is another option. Among the requirements are low mass, low power, 2-axis scan mirrors with 2” pointing precision and low mass, low power cryocoolers in addition to onboard lossless data compression.

Dropsondes were also discussed for measuring atmospheric properties including ozone. In this scenario, mass reduction of dropsondes (including capability for ozone measurements) by a factor of 4-5 is needed to allow thousands of dropsondes on a single platform such as a long-duration balloon.

Trace Gases, CO_2, Methane For the measurement of CO_2 and methane, several options exist such as laser absorption spectrometer or CO_2 DIAL (both in IR) from LEO. Requirements are high power, efficient laser transmitters, and greater than 50% detector QE. Another option is the use of Lagrange solar occultation spectrometer from L2 currently under development supported by the NASA IIP. Stable 8 m boom, optical stability to 0.1 micron and pointing stability and knowledge to 0.25” over 10 seconds are among the many requirements.

A GEO CO imager (based on the heritage of MAPS on Shuttle or MOPITT) provides another option. From a nadir view, this sensor identifies the emission, transport, and eventual cleaning of tropospheric pollution by measurement of CO. The sensor should be capable of handling large diurnal thermal swings and high radiation environment at GEO.

The use of an IR spectrometer on polar LEO, GEO, or ISS platform provides other opportunities. Lightweight, thermally stable (77-300K) materials for optics and mounts and long lifetime space coolers are needed.

Aerosols, Cloud Properties, & Cloud System Structure The scenarios discussed for the measurement of aerosol and their properties, cloud properties and cloud system structure included the use of a variety of lidars from LEO or airborne platforms, enhanced multi-angle, multi-spectral imaging spectroradiometers, and aerosol polarimeters from LEO, and IR spectrometers from GEO. For these options, enhanced technologies to reduce mass, power, size of sensors by a factor of 3 are needed. Improved methods for radiometric calibration are also desired.

Another scenario is the use of a cloud profiling radar from LEO. Deployable mm-wave antennas (> 2m) are needed for this scenario. Optical communication is also an enhancing capability.

Solar UV Irradiance With regards to the measurement of solar UV irradiance, the technology options include UV grating spectrometer and broadband radiometer. Technology to reduce mass, and power, improved performance and improved calibration accuracy are needed.

More detailed technology requirements can be found in chapter 3 of this report.

Table 1: Summary of Atmospheric Composition Science Theme Requirements

Science Requirement	Description	Measurement Requirements	Horizontal Resolution	Vertical Resolution	Revisit Rate	Coverage	Spectral Resolution	Accuracy
Volcanic gas and ash emissions	Measure volcanic gas and ash emissions to determine their effects on global climate.	need to characterize tropospheric constituents, column ozone, column SO2, ash, dust, smoke, cloud top height, thermal anomalies	<5km	NA	temporal resolution 5minutes	global		cloud top height 30mb; thermal anomalies 5 K
Solar UV irradiance	Conduct long-term monitoring of spectrally resolved solar ultraviolet irradiance, which affects stratospheric ozone and temperature.	spectrally resolved monitoring of solar UV radiation	NA	NA	1/day (1 hr min)	NA	1-2 nm over 120-6000 nm range	3% absolute radiometric; 1% consistency over solar cycle
Total aerosol amount	Conduct global observations of total aerosol amount, which has a significant effect on atmospheric temperature.	Total aerosol optical depth and single scattering albedo	<5 km	NA	1/day	global		10% of optical depth, 5% of scattering albedo
Stratospheric aerosol distribution	Conduct global observations of aerosol distribution with good vertical resolution.	stratospheric aerosol loading/extinction, profile and optical parameter chemical composition, density, particle size	10-50km	500m	1/day	global		10% of optical depth
Aerosol properties	Conduct in-situ and ground-based measurements of aerosol properties.	Total aerosol optical depth, single scattering albedo, chemical composition	NA	NA	hourly	global		10% of optical depth, 5% of scattering albedo
Surface trace gas concentration	Conduct in-situ measurements of total atmospheric concentrations of long-lived trace gases such as carbon dioxide, methane, nitrous oxide, and CFCs, which trap IR radiation and contribute to global warming.	Determine concentrations of long-lived surface trace gas as noted via in-situ measurements	NA	NA	daily	global		1%
Atmospheric properties in the tropopause	Conduct a detailed investigation of the relationship between ozone distribution, water vapor, aerosols, temperature, and trace constituents (chlorine, bromine, nitrogen oxide) in the tropopause. The highly complex, interactive relationships between these factors could reinforce and accelerate ozone layer destruction.	measure several parameters as noted in the tropopause region	50 km	500 m	daily	global		1%
Total column ozone	Conduct long-term total column measurements of stratospheric ozone and key factors governing its abundance, such as chlorine, bromine, CFCs, halogens, aerosols, methane, nitrous oxide, and water vapor.	measure stratospheric ozone column over long-term for trend studies	5 km		1/day	global		1%
Ozone vertical profile	Conduct long-term vertical profile measurements of stratospheric ozone and key factors governing its abundance, such as chlorine, bromine, CFCs, halogens, aerosols, methane, nitrous oxide, and water vapor.	measure vertical profile of ozone	50 km	500 m	daily	global		1%

Table 1 (continued)

Science Requirement	Description	Measurement Requirements	Horizontal Resolution	Vertical Resolution	Revisit Rate	Coverage	Spectral Resolution	Accuracy
Tropospheric ozone and precursors	Conduct global observations of tropospheric ozone, nitrogen oxides, carbon monoxide, hydrocarbons, and aerosols to understand the large-scale transport, removal, and chemical transformation of air pollution.	distribution of tropospheric ozone and other trace gases	5 -50 km	1 -5 km	1/day	global		ozone 1%; other 5%
Total solar irradiance	Measure variations in total solar irradiance, which could have important consequences for the Earth's climate.	measure variations in total solar irradiance over long periods	NA		1/day			<1%
Earth radiation budget	Measure radiation flows at the top of the atmosphere to relate cloud dynamics and properties to climate change. Cloud processes affect climate by controlling planetary radiation balance and, indirectly, through vertical transport and condensation of water vapor and the greenhouse effect.	measure broadband radiation; need to resolve diurnal cycle over a period of 2 months	30km		2/day	global		1%
Cloud system structure	Conduct observations which resolve the 3-dimensional structure of cloud systems. Cloud processes affect climate by controlling planetary radiation balance and, indirectly, through vertical transport and condensation of water vapor and the greenhouse effect.	measure cloud top height, temperature, humidity, cloud droplet size	10 km	30m	10/day	global		
Cloud particle properties and distribution	Conduct observations which cover a representative sample of all different cloud types and distributions of condensation nuclei and aerosol particles that affect cloud particle distributions. Cloud processes affect climate by controlling planetary radiation balance and, indirectly, through vertical transport and condensation of water vapor and the greenhouse effect.	measure particle density & size; ice & water content, albedo, optical depth	1-10km	30m	1/day	global		10% of optical depth

Table 2: Summary of Atmospheric Composition Theme Measurement Scenarios

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
Atmospheric Properties in the Tropopause, Total Column Ozone, Ozone Vertical Profile	RF Occultation Radiometer	Microwave, mm Band	MLS	Two spacecrafts in LEO	Measure vertical profiles of water vapor, temperature and various atmospheric constituents by a rising or setting pair of spacecrafts using the atmospheric occultation technique with < 1km vertical resolution and 200km horizontal resolution.	Ability for onboard processing of huge data volume; navigation accuracy to 20 cm; pointing accuracy to 1mrad
	UV DIAL	UV	Groundbased and airborne UV DIAL	One spacecraft in highly inclined LEO	Measure vertical profiles of tropospheric ozone, trace gases and tropospheric pollution in the mid-latitudes with 100km spatial resolution and IFOV < 100m.	Deployable 3-6 m class telescope; high power, compact UV laser to penetrate stratospheric O3 laser; high efficiency 1 micron pump lase with > 0.5 J, 5 Hz, high spectral purity ~99%, filter width 0.2 nm FWHM
	Solid State Linear Variable Etalon IR Spectrometer	LWIR	CLAES, CHRISTA, MIPAS, HIRDLS	One spacecraft in polar sun-synchronous orbit	Conduct long-term measurements of the vertical profile of ozone, aerosols, and trace gases in > 10 spectral bands.	Low mass, low power, 2-axis scan mirror with 2" pointing precision; low mass, low power cryocooler capable of cooling > 0.5W to 40K; pointing stability to 2"/s, knowledge 2", control 16"; onboard low loss data compression; selectable onboard data processing
	Broadband Spectrometer	UV/Vis/IR	SAGE III, MSX	One spacecraft in polar orbit or ISS platform	Measure global profiles of atmospheric aerosols, trace gases and ozone vertical profile using the solar/lunar/stellar occultation technique.	2D array detectors with small (~10 micron) pixel size, large full well (> 10^7 e-) and fast (> 100 Hz) operation; DSP chip speed increase by an order of magnitude with power consumption to 5 W
	Multi Waveband (Imaging) Spectrometer	UV/Vis	TOMS	One spacecraft in LEO or GEO	Measure tropospheric pollution, stratospheric ozone, and trace gases with 1km spatial resolution in > 12 bands with 1nm spectral resolution.	Rad hard CCD or CCD hybrid detectors; better than 1000:1 signal to noise ratio; advanced onboard lossless data compression; advanced onboard spectral analysis for hyperspectral data
	Microwave Limb Sounder	180GHz-2.5THz	UARS and Aura MLS	One spacecraft in LEO	Measure tropospheric ozone and precursors with global coverage and revisit time twice daily, horizontal resolution of 20-200km and vertical resolution of 1-3km (depending on the size of antenna chosen for flight).	Antenna system capable of fast scanning Earth's limb for specified resolution; cryocooler for 10mW heat load at T=4K with overall power consumption of < 150 W
	Dropsonde	NA	NCAR GPS dropsonde	Constellation of stratospheric long-duration balloons	Measure atmospheric temperature, water vapor, ozone, and winds from stratosphere to surface with an accuracy of 1% at > 20km using a meteorological dropsonde deployed from long duration balloons.	Mass reduction of dropsonde (including capability for ozone measurement) by a factor of 4-5 to allow 1000s on a single platform; long duration balloons with trajectory control system
CO2, Methane, & Trace Gases	Laser Absorption Spectrometer (LAS)	IR	Airborne LAS	One spacecraft in LEO	Determine distribution of CO2 abundances in the lowermost 5km of the troposphere via integrated path differential absorption (PDA) method with precision of 1-2ppm and vertical resolution of 1-2 km.	2-micron, 2-5 W cw power, rare-earth ion-doped solid state lasers capable of frequency stabilization to +/- 2 MHz and >2% wallplug efficiency; improved heterodyne quantum efficiency detectors; 75 cm telescope aperture
	CO2 Differential Absorption Lidar (DIAL)	IR	Airborne DIAL	One spacecraft in LEO	Provide low tropospheric CO2 mixing ratio profiles.	1-2 J, 20 Hz double pulsed lasers at 2.05 micron with spectral purity > 99.5% and wallplug efficiency > 5% and cooled near 20 deg C; deployable telescope > 3 m diameter; detector QE > 50%; thermal dissipation capability in excess of 40 kW

Table 2 (continued)

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
	Lagrange Solar Occultation Spectrometer (coupled to Fizeau Interferometer)	NIR/SWIR/MWIR	Current development under NASA IIP	One spacecraft in L2	Obtain altitude, latitude, and longitude distribution of greenhouse gases using solar occultation from L2.	Stable 8 m boom; optical path stability to 0.1 micron; Pointing stability and knowledge to 0.25" over 10 seconds
	GEO CO Imager	SWIR/MWIR	MAPS, MOPITT, GeoTRACE design study, CISR design study	One spacecraft in GEO	Measure emission and transport of CO in > 20 spectral bands.	Sensor should be capable of handling large diurnal thermal swings, and high radiation environment at GEO; compact imaging optical system with 4km IFOV; long term stable (1% over 5 years) optical filters; large SNR> 2500; high speed data bus (100Mbps) in space; pointing stability 2 microradians
	IR Spectrometer	IR	ATMOS, Aura/TES	One spacecraft in polar or GEO orbit, or ISS platform	Measure atmospheric composition and gas concentrations in the troposphere, stratosphere and mesosphere.	Thermally stable (77-300K) materials for optics and mounts lighter than aluminum; long life space qualified 77k cryocoolers or uncooled detectors covering the 17-3 um wavelength range; long life space stabilized (dnu/nu < 5E-8) metrology lasers
Aerosol Amount & Properties, Cloud Particle Properties & Distribution, Cloud System Structure	Variety of Lidars	UV/Vis/IR	LITE, CALIPSO, Airborne DIAL	One spacecraft in LEO; or Airborne Platforms	Measure stratospheric aerosol distribution and cloud properties with high spatial and vertical resolution in multi wavebands from UVI to IR using a variety of spaceborne or airborne lidars.	Technology to reduce mass, power, size, and cost of instrument; small laser transmitter system with wallplug efficiency > 10%; detector QE > 50%; stable, narrowband, tunable filters (10GHz full width half max, 90% transmittance)
	Multi-Angle Spectroradiometer	Vis/IR	MISR	One spacecraft in LEO	Provide multiple-angle coverage of the Earth with high spatial resolution with data on aerosol sampling, cloud properties and planetary radiation budget.	Technology to reduce mass and size by a factor of 3; improved angle-to-angle absolute radiometric calibration
	Aerosol Polarimeter	Vis/IR	Aerosol Polarimetry Sensor (APS), Pioneer Venus/CPP, Galileo Orbiter/PPR	One spacecraft in LEO	Measure aerosol properties in 12 bands using a multi-spectral, multi-angle polarimeter which provides data on optical depth, single scatter albedo, particle size and shape, and refractive index .	Technology development to reduce cost, size, mass, and power.
	Multi-Spectral Imaging Spectroradiometer	Vis/IR	Terra & Aqua MODIS, NPOESS VIIRS	One spacecraft in LEO	Measure atmospheric aerosol, cloud droplet size and optical depth in 36 bands with a spatial resolution of 250m at nadir and swath width 2300km.	Improved method for radiometric calibration of IR bands in a pushbroom instrument; narrow bandwidth optical filters (0.2% of center wavelength); large format FPAs with improved noise properties, and high QE; uncooled IR FPAs or IR detectors with modest cooling requirements
	Geosynchronous IR Fourier Transform Spectrometer	IR	HIS/GHIS, NAST-I, AIRS, NMP EO-3/GIFTS	One spacecraft in GEO	Measure cloud system structure and ozone with spatial resolution of 4 km x 4 km, vertical profile resolution of 2 km, and spectral resolution of 0.3 cm-1 or greater.	Thermally stable (~77-300k) optics and mount material lighter than aluminum; long lifetime space qualified 77 cryocoolers and/or background limited uncooled detectors; long lifetime space qualified stabilize (dnu/nu < 5E-7) metrology lasers; high rate and low power DSP electronics and data compression techniques
	Geosynchronous IR Spectrometer	MWIR/LWIR	GOES Imager	One spacecraft in GEO	Image volcanic gas and ash clouds and measure ash cloud height and temperature in multiple bands with spatial resolution of < 5km and pointable with revisit time of 5 minutes.	Fast thermal scanner, rad hard CCD; optical filters such as Acousto-Optical Tunable Filter (AOTF); low volume microbolometer arrays or array cooling

Table 2 (continued)

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
	Cloud Profiling Radar/Dual Frequency Radar	94 GHz; 94 & 140 GHz	Airborne Cloud Radar, CloudSast/CPR	One spacecraft in LEO	Measure cloud particle and cloud system structure using a mm-wave radar with spatial resolution of 3.5 km and vertical resolution of 500m. Dual frequency option allows increased sensitivity to the thin cirrus clouds.	Technology to reduce mass, size, power; deployable mm-wave antenna (> 2m); optical communication is enhancing
	Sub-mm/Far IR Radiometer	Sub-mm/Far IR	Limb Sounding Radiometers	One spacecraft in LEO	Measure cloud systems using a sub-mm wave radiometer in 8 bands.	Technology development of 1 THz oscillators to allow combination of submm and far IR sensors into a single instrument; deployable mm-wave antenna
	IR Differential Absorption Lidar (DIAL)	IR	LASE and other ground based or airborne measurements	One spacecraft in LEO	Measure sratospheric aerosol profiles and atmospheric temperature using an IR DIAL.	Small, efficient DIAL system with energy > 1J, pulse at 10Hz, narrow linewidth (99.5%), pumping by conductively cooled diode lasers and > 8% overall power efficiency
Solar UV Irradiance, Total Solar Irradiance, Earth Radiation Budget	UV Grating Spectrometer	UV	SORCE/SOLSTIC E	One spacecraft in LEO	Measure solar UV irradiance in the region 115-300nm with spectral resolution 0.1 nm (for the Sun) and absolute accuracy of 5%.	Technology enhancement to reduce mass and power and improve performance from SOLSTICE
	Broadband Radiometer	UV/Vis/IR	CERES, ERBE	One spacecraft in LEO	Measure total solar irradiance and UV spectral irradiance with enhanced spectral resolution in the range 100-600nm. Type radiometer can also be used to measure broadband Earth radiation budget.	Broadband radiometer detector development with optical filter; high calibration accuracy; broad spectrum

2.2 Carbon Cycle

Table 3 shows a summary of the science requirements for the carbon cycle theme. These requirements were provided by the cognizant ESE program scientists at NASA HQ.

Based on the science requirements presented in Table 3, a total of 23 measurement scenarios were discussed and validated at the workshop. These detailed scenarios and their corresponding technology requirements can be found in ESTIPS by searching the "Science Drivers" -> "Carbon Cycle" theme. A summary of the technology options and corresponding needed capabilities for this theme appears in Table 4.

Land Cover & Use, Terrestrial Productivity, Biomass For the measurement of land cover/use, terrestrial productivity, biomass and fire occurrences, one technology option is the use of advanced multispectral or hyperspectral imagers in visible/IR bands from LEO. In general, reduction in mass, power and size of the sensors are cost enabling. Furthermore, large format FPAs with improved noise properties, and high QE, as well as improved atmospheric correction and calibration accuracy are needed for this application. Also spectrometers better than F/2 with improved detector response, and optics with low scatter and polarization (<1% and <2%, respectively) in addition to long life space qualified cryocoolers are needed. For the hyperspectral option, data rates can be in excess of 1Gbps. Therefore, approaches for lossless compression and onboard processing are needed.

Another technology option for the type of measurement is the use of polarimetric synthetic aperture radar (SAR) in the L-band from LEO. For this option, lightweight (<6kg/m^2) antenna, high efficiency (>60%) T/R module, and pointing knowledge and control to 0.05 deg and 0.1 deg, respectively, are needed.

Terrestrial & Marine Productivity For the measurement of terrestrial and marine productivity, a land/ocean productivity lidar (with heritage from airborne lidars) on a LEO platform is an option. Compact, joule-class, solid state laser transmitter with > 5% wallplug efficiency along with meter-class lightweight optics are needed.

A particulate organic carbon lidar (based on airborne laser bathymetry) from LEO or airborne platforms is another option. For this scenario, laser penetration to depth of 100m requires operation in the blue/green spectral region. Eye safety requirements must be traded against SNR for rendering a measurable signal. Combination of meter class optics and photon counting detection is needed to make this scenario feasible. However, the most feasible platform in the next 5-10 years is airborne.

Marine Productivity in Coastal Regions Measurement of marine productivity in coastal regions could be achieved via coastal ocean hyperspectral imager or high resolution imagers from GEO. Large aperture (1m) scanning telescope with lightweight mirrors (<8kg/m^2) and attitude knowledge and control to 0.0001 deg and 0.01 deg, respectively, and stability to 0.00002 deg are needed. Long lifetime (> 7 years) CCD and filters are also desired. Onboard information technology to handle greater than 100 Mbps data rate and data storage in excess of 1 Gb is also needed.

Vegetation Biomass The measurement of vegetation biomass can be achieved via several options including a vegetation polarimetric SAR in P band (from LEO), repeat pass interferometric SAR in L band (from LEO or UAV platform) and laser altimetry in visible/NIR from LEO. The requirements are lightweight (<2kg/m^2), mesh or inflatable stretch antenna for the radar options, and high efficiency, high power laser transmitter with high detector QE (> 15%) for the laser option.

Growing Season Length The freeze-thaw transition to measure the growing season length at > 40 deg northern latitudes can be accomplished via a cold land dual frequency SAR. Deployable mesh or inflatable antennas are needed.

CO_2 & Methane Finally, for the measurement of CO_2 and methane, several options exist such as laser absorption spectrometer or CO_2 DIAL (both in IR) from LEO. Requirements are high power, efficient laser transmitters and greater than 50% detector QE. Another option is the use of Lagrange solar occultation spectrometer from L2 currently under development supported by the NASA IIP. Stable 8 m boom, optical stability to 0.1 micron and pointing stability and knowledge to 0.25" over 10 seconds are among the many requirements.

More detailed technology requirements can be found in chapter 3 of this report.

Table 3: Summary of Carbon Cycle Science Theme Requirements

Science Requirement	Description	Measurement Requirements	Horizontal Resolution	Vertical Resolution	Revisit Rate	Coverage	Spectral Resolution	Accuracy
Trace gas sources	Measure trace gases (including naturally occurring and industrially produced), especially CO2 column mapping, to determine the potential for climate change.	Total column CO2 including tropospheric CO2	<10km	for profiles, 1km to discriminate boundary layer	1-2 days, revisit same spot twice in 1 day to remove bias	global	N/A	0.30%
Terrestrial primary productivity	Measure variations in productivity, composition, and health of global ecosystems, which produce food and fiber for human use, govern changes in the Earth's carbon cycle, and modulate the water cycle over land. The desired parameters can be derived from measurements of chlorophyll concentration and vegetation index.	crop/forest yields, photosynthesis, respiration, carbon sequestration	5-20 m	N/A	seasonal	global	multi to hyper	sufficient to discriminate year to year changes
Land cover and land use	Conduct systematic global multispectral mapping of land cover once or a few times per year to generate periodic global inventories of land cover and land use for land usage/management practices.	land cover types, land cover change	10-30m with 1m sampling	N/A	6/year	global	multi to hyper	N/A
Land cover and land use	Conduct systematic global multispectral mapping of land cover once or a few times per year to generate periodic global inventories of land cover and land use for lan usage/management practices.	coarse resolution land cover types, land cover change	250m-1km	N/A	6/year	global	multi to hyper	N/A
Biomass	Quantify the responses of terrestrial ecosystems to disturbance in terms of (above-ground) biomass changes and consequent carbon sequestration or emission. Responses may include changes in physiology, biogeochemical cycling, species composition, biomass density, canopy architecture, and distribution patterns.	vegetation &phytoplankton dynamics; vegetation structure & density	5-20m	0.5m	seasonal	global	active microwave or optical	N/A
Marine productivity in coastal regions	Observe ocean color to determine the productivity of marine ecosystems in coastal regions. This will resolve weather-induced changes and tidal fluxes, which quantify variability in the primary biological productivity of coastal regions. Coastal regions are highly productive and extremely variable. They affect the biological pump which is a critical component of the ocean carbon cycle and affects the balance of carbon dioxide (a greenhouse gas) between the atmosphere and the ocean. Because of the smaller scale and rapid changes, this need is distinct from marine primary productivity.	primary productivity, biomass, chlorophyll, absorbance of chromophoric dissolved organic matter and detritus, dissolved organic carbon (DOC), dissolved inorganic carbon, particulate organic carbon, particulate inorganic carbon, terrestrial DOC flux, algal DOC production, phytoplankton pigments, taxonomy, physiology and photosynthetic activity, phenology, algal blooms, start/end growing season, mixed layer depth, photosynthetically available radiation	30-100m	N/A	1-3/day	regional	5-15nm	N/A

Table 3 (continued)

Science Requirement	Description	Measurement Requirements	Horizontal Resolution	Vertical Resolution	Revisit Rate	Coverage	Spectral Resolution	Accuracy
Marine primary productivity	Conduct global observations of the spatial distribution, extent, and temporal dynamics of marine productivity with moderate-resolution multispectral images at near-daily frequency. Ocean color is the primary means of measuring marine productivity. Peaks in marine primary productivity (blooms) usually occur when oceanic motions bring nutrient-rich waters into the well-lit upper oceans. Such events often dominate the downward flux of organic carbon.	primary productivity, biomass, chlorophyll, absorbance of chromophoric dissolved organic matter, dissolved organic carbon (DOC), dissolved inorganic carbon, particulate organic carbon, particulate inorganic carbon, algal DOC production, phytoplankton pigments, taxonomy, physiology and photosynthetic activity, mixed layer depth, photosynthetically available radiation	<500m	N/A	1/day	global	10-20nm	N/A
Fuel quantity and quality	Conduct global observations in IR, Vis/NIR, and hyperspectral to determine fuel load.	fuel moisture/canopy openness, fuel mass, quantity, quality, location	30m	<0.5	weekly during fire season, but only needed seasonally otherwise	regional to global	either active optical or active microwave	better than MODIS
Fire occurrences and extent	Conduct global observations in IR, Vis/NIR, and hyperspectral to determine fire occurrence.	Fire intensity, extent, and location; Smoke column quantity and quality	100m -km	N/A	weekly during fire season, but only needed seasonally otherwise	regional to global	multi/thermal	better than MODIS
C02 and methane	Conduct precise measurements of spatial, temporal, and (perhaps) vertical variations in total column amount of carbon dioxide and methane in the atmosphere in order to quantify regional carbon sources and sinks. These measurements are important for understanding the global carbon cycle and predicting future climate changes.	Total column CO2 including tropospheric CO2	<10km	for profiles, 1km to discriminate boundary layer	1-2 days, revisit same spot twice in 1 day to remove bias	global	N/A	0.30%
Coastal region properties and productivity	Conduct repeated multispectral observations of coastal regions (beaches, low lying land areas near oceans, estuaries and river deltas) at the highest practicable spatial and temporal resolution to provide information on the distribution and properties of biological material. These regions are important because their human population is fast increasing and the regions are particular susceptible to climate and sea level changes.	primary productivity, chlorophyll, absorbance of chromophoric dissolved organic matter and detritus, dissolved organic carbon (DOC), dissolved inorganic carbon, particulate organic carbon (POC), particulate inorganic carbon, terrestrial DOC and POC flux, black carbon, phytoplankton taxonomy	<30-100m	N/A	1-5/day	regional	multi to hyper	N/A
Growing season length in high latitudes	Conduct daily measurement of freeze/thaw conditions in high latitudes to estimate growing season length	freeze/thaw	1km	N/A	daily	regional	radar	N/A

Table 4: Summary of Carbon Cycle Theme Measurement Scenarios

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
Land Cover & Use, Terrestrial Productivity, Biomass, Fire Occurrences	Multispectral Imaging Spectroradiometer	Vis/IR	Terra & Aqua MODIS, NPOESS VIIRS	One spacecraft in LEO	Measure variety of parameters including land cover and use, terrestrial productivity, biomass, and fire occurrences in 36 bands, with 250 m spatial resolution at nadir, IFOV 250-1000m, and swath width 2300 km.	Large format FPAs with improved noise properties, high QE; improved atmospheric correction; improved calibration accuracy; narrow bandwidth (0.2% of center wavelength) optical filters
	High Resolution Multispectral Imager	Vis/IR	Landsat ETM	One spacecraft in LEO	Measure land cover and use in 15 bands between 0.4-2.5 microns with 10 m (panchromatic) and 30 m (multispectral) spatial resolution.	Reduction in mass, power, and size with similar performance to Landsat 7/ETM+
	Earth Surface Hyperspectral Imager	Vis/IR	EO-1/Hyperion	One spacecraft in LEO	Measure Earth surface reflectance and emittance to detect molecular and scattering signatures related to vegetation type, health, amount, and surface composition and chemistry in > 220 bands with 30 m spatial resolution and 100 km swath.	Spectrometers better than F/2; improved detector response at < 400nm; optics with low scatter (< 1%), low polarization (< 2%), improved stability (<1%) over months; low cost, low CTE material; cryo cooler to < 120 K with 1 W in LEO; 1Gbps data rate
	Polarimetric SAR	L Band	AirSAR, GeoSAR, SRTM, ALOS/PALSAR, JERS-1	One spacecraft in LEO	Determine land cover types, including wetlands type/extent/dynamics, vegetation characteristics such as moisture, density and height with 25 m spatial resolution. For the repeat-pass option, need better than 100-200m accuracy repeat track and in < 10 days.	Lightweight (< 6kg/m^2) antennas; high efficiency (> 60%) T/R modules; pointing knowledge to 0.05 deg, control to 0.1 deg
Vegetation Biomass	Vegetation Polarimetric SAR	P Band	SIR-C, Radarsat	One spacecraft in LEO	Measure vegetation biomass up to at least 200 tons/ha with accuracy of 5 tons/ha, spatial resolution of 25-50 m with semi-annual repeat global mapping.	Lightweight (< 2kg/m^2), size ~12m x 3-5m, mesh or inflatable stretch antennas; high efficiency (> 60%), low mass (<50g) T/R modules
	Repeat-pass INSAR	L Band	AirSAR, GeoSAR, SRTM, ALOS/PALSAR, JERS-1	One spacecraft in LEO; or Mounted on UAV	Determine vegetation characteristics (height and density profile) with repeat-pass SAR interferometry, single to quad polarization.	Light antenna (< 6 kg/m^2); for spaceborne option pointing knowledge 0.05 deg, control 0.1 deg; for airborne option precise knowledge of motion and location (0.01 deg roll/pitch, 0.03 m/s velocity, 10 cm location) and maintain baseline stability within a 5-10 m tube
	Laser Altimeter	Vis/IR/NIR	Airborne IIP Microlaser Altimeter, ICESat/GLAS, MOLA, or LVIS	One spacecraft in LEO	Map surface elevation, vegetation height and vertical structure, river stage height and ice topography.	Multiple Laser Options; e.g. 532 nm Laser pulse width < 1ns and wallplug efficiency > 3%; array detector with single photon sensitivity and subnanosecond rise time, < 5 n; detector QE > 15%; narrow bandwidth filters
Terrestrial and Marine Productivity, Land Cover & Use	Land/Ocean Productivity Lidar	UV/Vis	Airborne Lidars (e.g. AOL)	One spacecraft in LEO	Measure terrestrial and ocean productivity via laser induced fluorescence (LIF) of compounds diagnostic of plant health to assess photosynthesis and environmental stress.	Compact, efficient, joule-class, solid state Nd:YAG laser transmitters; high efficiency (> 95%) solar radiation rejection filters; meter-class lightweight optics
Marine Productivity	Particulate Organic Carbon Lidar	Vis	Airborne Laser Bathymetry	One spacecraft in LEO; Airborne	Measure particulate carbon and its profile in the upper 100 m ocean layer.	Penetration to depth of 100m requires operation in the blue/green region of spectrum. Eye safety requirements must be traded against SNR for rendering a measurable signal. Combination of meter class optics and photon counting detection needed to make this scenario feasible. Most feasible platform in 5-10 years is airborne.

Table 4 (continued)

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
Marine Productivity in Coastal Regions	High Resolution Event Imager	Vis/NIR	Terra & Aqua MODIS, NPOESS VIIRS	One spacecraft in GEO	Measure algal bloom and dynamic properties in coastal waters with high spatial (100m) and temporal resolution (15 min. repeat), and 5-15nm spectral resolution and 14 degrees field of regard.	Large aperture (1m) scanning telescope with lightweight mirrors (< 8 kg/m^2); attitude knowledge of 0.0001 deg, control 0.01 deg, and stability 0.00002 deg (the latter being the driving requirement); CCD and filter lifetime > 7 years in orbit
	Coastal Ocean Hyperspectral Imager	Vis/NUV	Hyperion/EO-1	One spacecraft in GEO	Measure coastal ocean primary productivity in the spectral range 350-1050 nm with 5 nm spectral resolution in > 140 bands and < 200 m spatial resolution, > 200 Km swath.	Pointing accuracy better than 1 microradian; low polarization optics (< 2%); spectrometers better than F/2; >0.5 m aperture optics with < 1% scatter; improved detector response < 380 nm; 100 Mbps data rate; data storage > 1 Gb
Growing Season Length	Cold Land Dual Frequency SAR	L Band	Seasat SAR, SIR-C/X-SAR, LightSAR, AIRSAR	One spacecraft in polar sun-synchronous orbit	Measure freeze-thaw transition at > 40 deg northern latitudes with 1km spatial resolution, 700 km swath, 2-day repeat.	Deployable mesh or inflatable antennas, size ~ 10-15m x 2-3m, areal density < 2kg/m^2, high efficiency (> 60%), low mass (<50g) T/R modules; pointing knowledge and control 0.5 degrees; data rate ~ 18Mbps
CO2 & Methane	Laser Absorption Spectrometer (LAS)	IR	Airborne LAS	One spacecraft in LEO	Determine distribution of CO2 abundances in the lowermost 5km of the troposphere via integrated path differential absorption (PDA) method with precision of 1-2ppm and vertical resolution of 1-2 km.	2-micron, 2-5 W cw power, rare-earth ion-doped solid state lasers capable of frequency stabilization to +/- 2 MHz and >2% wallplug efficiency; improved heterodyne quantum efficiency detectors; 75 cm telescope aperture
	CO2 Differential Absorption Lidar (DIAL)	IR	Airborne DIAL	One spacecraft in LEO	Provide low tropospheric cO2 mixing ratio profiles.	1-2 J, 20 Hz double pulsed lasers at 2.05 micron with spectral purity > 99.5% and wallplug efficiency > 5% and cooled near 20 deg C; deployable telescope > 3 m diameter; detector QE > 50%; thermal dissipation capability in excess of 40 kW
	Lagrange Solar Occultation Spectrometer (coupled to Fizeau Interferometer)	NIR/SWIR/MWIR	Current development under NASA IIP	One spacecraft in L2	Obtain altitude, latitude, and longitude distribution of greenhouse gases using solar occultation from L2.	Stable 8 m boom; optical path stability to 0.1 micron; Pointing stability and knowledge to 0.25" over 10 seconds

2.3 Climate Variability & Change

Table 5 shows a summary of science requirement for the climate variability theme provided by the cognizant ESE program scientists at NASA HQ.

Based on the science requirements presented in Table 5, a total of 19 measurement scenarios were discussed and validated for this theme at the workshop. These detailed scenarios can be found in ESTIPS by searching the "Science Drivers" -> "Climate Variability" theme. A summary of the technology options and corresponding needed capabilities to meet the science requirements for this theme appears in Table 6.

Ocean Surface Topography For the measurement of ocean surface topography, radar altimetry in the Ka band from LEO based on the heritage of Topex/Poseidon and Jason is a proven option. However, new capabilities in addition to reduced mass & size relative to Jason's altimeter is needed to achieve 1cm ocean height accuracy.

Another option is the use of a bistatic radar on a constellation of spacecrafts in LEO where surface height is measured from timing of direct vs. reflected GPS signals. Low cost, high precision, high gain, steerable, multi-beam (~10) antenna systems, in addition to the ability to process large data volumes (up to 10 simultaneous reflection and uplooking GPS tracking data) are needed.

Ocean Circulation & Mixed Layer Depth For the measurement of mesoscale eddy structure and 2D ocean circulation, interferometric radar altimetry in the Ku band is an option. For this scenario, interferometric boom stability, lightweight deployable antennas and mature TWTA technology (advances from 120 W to 500 W) are needed. Also improvements in star tracker technology by a factor of 5 and attitude knowledge to 0.01'' and onboard compression processor (20,000:1 compression ratio) are needed. Optical communication is an enhancing capability.

For the measurement of the ocean mixed layer depth, ocean mixed layer lidar based on the heritage of airborne bathymetry is an option. High energy pulsed blue/green laser source is needed in this scenario. However, eye safety requirements must be traded against SNR for rendering a measurable signal. Combination of meter class optics and photon counting detection is required. Because of these restrictions, aircraft deployment is more feasible within 5-10 years.

Sea Surface Salinity Measurement of sea surface salinity can be achieved via several options from LEO including the 2D synthetic thinned aperture radiometer (STAR), large real aperture antenna radiometer and scatterometer, and the very large real aperture mesh antenna radiometer. Effective aperture of 10-20 m as well as radiometer stability to ~0.1K is needed for the STAR option. For the real aperture option, rotating (~5m and ~25, respectively, for the large and the very large options) deployable antennas with high reflectivity (>0.99) are needed. Ability to control and stabilize large rotating mesh antennas is crucial.

Sea Surface Temperature Sea surface temperature can be measured via multi-spectral imaging spectroradiometers in the visible/IR band based on the heritage of Terra and Aqua MODIS and NPOESS VIIRS. Narrow bandwidth optical filters, in addition to uncooled IR FPAs (or improved IR detectors with modest cooling), as well as improved radiometric calibration accuracy are needed.

Sea Ice Extent & Polar Ice Sheet Velocity Sea ice extent and polar ice sheet velocity can be measured via a variety of approaches including the real aperture scatterometer in Ku band, repeat pass InSAR in L band, and SAR altimeter in C band, all from LEO platforms. The requirements are large antenna apertures of low mass density (<6 kg/m^2) and reduction in power, size and mass of the instruments relative to state of art, and tight pointing and control and knowledge to 0.05 deg. Optical communication is an enhancing capability.

Sea Ice Thickness & Sea Ice Topography Measurement of sea ice thickness and ice surface topography can be achieved by several options. Sea ice InSAR in the Ka band from LEO is an option. Requirements are lightweight (< 5kg/m^2) electronic scanning antennas, sea-ice thickness retrieval algorithms, and a rigid 10 m interferometric mast. Precision metrology for antenna and mast is crucial.

Bistatic interferometric radar in VHF from LEO is another approach. For this scenario, cylindrical reflector with dual polarization combined with Ku band phased array feed is needed.

Laser altimetry from LEO is another option. In this case, high power, efficient laser sources, meter class optics, pointing knowledge to better than 1", and ability to dissipate multi kW heat loads on orbit are needed.

Another option is the use of a VHF radar mounted on a rover. Capability to autonomously perform transect of Arctic ocean ice for distances of at least 1000 km, monitor locations within 1km horizontally and 10cm vertically, and acquire ice thickness data of 5cm or 2% accuracy and communicate results back to the continent is required.

More detailed technology requirements can be found in chapter 3 of this report.

Table 5: Summary of Climate Variability Science Theme Requirements

Science Requirement	Description	Measurement Requirements	Horizontal Resolution	Vertical Resolution	Revisit Rate	Coverage	Spectral Resolution	Accuracy
Ocean surface topography	Measure global ocean surface height (altimetry) to determine changes in ocean circulation, which could have a significant effect on climate due to the enormous amount of heat stored in the ocean. Use global ocean surface height measurements to detect global sea level variations to test long-term prediction of sea level rise. Altimetry and gravity measurements also reveal changes in subsurface ocean temperature and heat storage.	measure ocean surface topography	5-10km		every 15 days	global		1 cm
Ocean Surface Currents	Study air/sea interactions coupled to coincident surface winds measurements. Detect El Nino and La Nina onsets with ocean current.	measure mixed scattering layer depth	100km	5-10m	weekly	global		5 cm/s
Sea surface salinity	Measure sea surface salinity to investigate the potential for changes in ocean circulation. The slow, massive overturning circulation of water from the surface to the ocean depths has profound implications for climate change, containment of excess chemicals, marine productivity, and the carbon cycle. The ability of surface water to sink into the deep ocean depends on salinity and temperature, which determine water density.	measure sea surface salinity	25km		every 5 days	global		0.2 psu
Deep ocean circulation	Use an ocean general circulation models to combine satellite observations of oceanographic variables at sea surface and of ocean gravity changes with in situ oceanographic observations of deep ocean circulation globally to improve the ability to assess and predict long-term climate trends.	combine satellite and in situ observations of oceanographic variables in general circulation models	100km	5-10 m in the upper 200m, 25-50m for depths 200-1000m, 100m for depths 1000-bottom	monthly	global		1 cm/s
Sea surface temperature	Measure global ocean surface temperature in order to model and predict natural climate variations such as El Nino and associated weather disturbances.	measure sea surface temperature	50km		every 5 days	global		<0.3K
Sea ice extent	Measure the extent of sea ice over polar oceans, which is a sensitive indicator of climate change. Recent observations indicate a decrease in sea ice extent and thickness in the Arctic, which could have a major amplifying effect on global warming in northern latitudes.	extent; concentration; age; salt content; albedo	1km	n/a	2/day	polar oceans	n/a	edge detection 1km; ice concentration < 5%
Ice surface topography	Measure topography of polar ice sheets, smaller ice caps and glaciers to determine changes in the Earth's ice cover, which is an important indicator of climate and exerts controls on climate which are not well understood.	Precise elevation, and changes in elevation with time	1 km - 100 km	1 m - 1cm respectively	achieved frequently through crossover analysis	polar regions	n/a	1 m - 1 cm respectively
Sea ice thickness	Measure sea ice thickness to investigate the potential for changes in ocean circulation, and changes in energy fluxes. Recent observations indicate a decrease in sea ice extent and thickness in the Arctic, which could have a major amplifying effect on global warming in northern latitudes.	ice thickness, surface snow depth seasonal changes	10km	< 5 cm	1/day	polar oceans	n/a	<5cm
Polar ice sheet velocity	Map the velocity fields of the great ice sheets of Greenland and Antarctica to estimate the rate at which the polar ice caps are changing. Melting of the polar ice sheets could lead to a significant rise in sea level around the world in a few years or decades.	Surface velocities and velocity gradients, particularly in fast-moving outlet glaciers, and changes in these velocities	1-10km	n/a	1/month	polar regions	n/a	10cm/s

Table 6: Summary of Climate Variability Theme Measurement Scenarios

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
Ocean Surface Topography, Circulation, & Surface Currents	Radar Altimeter	Ka Band	Topex/Poseidon and Jason altimeters	One spacecraft in LEO	Measure ocean surface topography with 5-10 km spatial resolution and height accuracy of 1cm.	35 GHz synthetic aperture altimeter with pulse repetition frequency 10 KHz and 600 MHz bandwidth; reduced mass, size, and power relative to Jason; pointing knowledge/control to 0.05 deg
	Advanced GPS Receiver for Altimetry; Bistatic Radar	GPS L1 and L2 Band	Blackjack design for software reconfigurable flight GPS receiver, Jason	One or constellation of spacecrafts in LEO	Measure ocean surface height from timing of direct vs. reflected GPS signals.	Low cost, high precision, high gain (~30dB), steerable, multi-beam (~10) antenna systems; ability to process multiple GPS antenna inputs; ability to process large data volumes (up to 10 simultaneous reflection + uplooking GPS tracking data)
	Interferometric Radar Altimeter	Ku Band	New Development	One spacecraft in LEO	Measure ocean mesoscale eddy structure and 2D ocean circulation, ocean surface height with 1cm accuracy, 200 km swath and 10m baseline.	Interferometric boom short term stability; lightweight deployable antenna; TWTA technology to mature from 120 W to 500 W; improvement in star tracker technology by a factor of 5; simultaneous co-located operation of a Doppler beacon receiver, GPS receiver, and a laser reflector array for precise orbit determination; attitude knowledge to 0.01''; onboard range compression processor (20,000:1 compression ratio); optical communication (enhancing capability)
	Ocean Mixed Layer Depth Lidar	Vis	Airborne Bathymetry	One spacecraft in LEO; or Airborne	Measure ocean mixed layer depth with 5m depth resolution or better.	High energy pulsed blue/green laser source; eye safety requirements must be traded against SNR for rendering a measurable signal; combination of meter class optics and photon counting detection required; aircraft deployment more feasible within 5-10 years
Sea Surface Salinity	2D Synthetic Thinned Aperture Radiometer (STAR)	L Band	GSFC ESTAR airborne radiometer	One spacecraft in LEO	Measure ocean salinity using a STAR radiometer with spatial resolution of 10km, 950 km swath, 2-3 day revisit time.	1.4 GHz STAR radiometer with 20 MHz bandwidth and dual polarization; effective aperture of 10-20m; radiometer receiver stability ~0.1K over several days; low power (< 0.2 W) per receiver element
	Large Real Aperture Antenna Radiometer and Scatterometer	L Band	Development in NASA IIP and Aquarius	One spacecraft in LEO	Measure ocean salinity to accuracy of 0.1 psu using a rotating real aperture radiometer with mesh antenna with 900 km swath and global coverage every 3 days.	Rotating (< 5rm), size ~25m diameter deployable antenna with beam efficiency > 92% and surface reflectivity > 0.99; radiometer stability of 0.1 K over 2-5 days
	Very Large Real Aperture Mesh Antenna Radiometer	L Band	IIP development, Aquarius Mission	One spacecraft in LEO	Measure ocean salinity with 40 km spatial resolution and 0.1 psu accuracy.	Rotating 25m diameter deployable antenna with mesh or inflatable design and high reflectivity > 0.995; ability to control and stabilize large rotating mesh antenna
Sea Surface Temperature	Multispectral Imaging Spectroradiometer	Vis/IR	Terra & Aqua MODIS, NPOESS VIIRS	One spacecraft in LEO	Measure sea surface temperature in > 36 bands with spatial resolution of 250-1000 m at nadir, and swath 2300 km.	Narrow bandwidth (0.2% of center wavelength) optical filters; uncooled IR FPAs or improved IR detectors with modest cooling requirements; improved cloud presence detection; improved radiometric calibration accuracy
Sea Ice Extent, Polar Ice Sheet Velocity	Real Aperture Scatterometer	Ku Band	NSCAT, QuikSCAT, SeaWinds	One spacecraft in polar LEO	Measure sea ice extent and ice motion with spatial resolution of 3-5 km, daily coverage and wide swath ~1200 km.	Dual polarization real aperture or Doppler beam sharpening scatterometer with large antenna aperture (> 5 m real aperture, > 3m Doppler sharpening capability); calibration techniques for Doppler sharpening scatterometer

Table 6 (continued)

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
	Repeat-pass INSAR	L Band	SeaSat, SIR-C, SRTM	One spacecraft in LEO	Measure polar ice sheet velocity using a repeat pass dual band INSAR to 1m/year accuracy and spatial resolution 5-25m and swath 100-300 km.	Electronically scanned array antenna of size ~ 14m x 3m with < 6 kg/m^2 and > 4KW peak transmit power; T/R module with > 60% efficiency; mass, power, and size reduction over state of art; orbit control to 200 m tube, pointing knowledge ~0.05 deg, control ~0.1 deg; optical communication is enhancing feature
	SAR Altimeter	C Band	ERS/AMI, METOP/ASCAT	One spacecraft in LEO	Measure sea ice motion, extent, concentration, and surface deformation with horizontal resolution of 25m and500 km swath, 3-8 day revisit time with precision of 10 cm or better, edge detection accuracy of 1 km, ice concentration accuracy of < 5%, snow depth accuracy of < 5cm.	Electronically scanned antenna size ~ 15m x 3m, lightweight < 6 kg/m^2; T/R module efficiency > 60%; reduction in power, size, and mass relative to state of art; pointing control/knowledge to 0.05 deg; optical communication is enhancing feature
Sea Ice Thickness, Ice Surface Topography	Sea Ice INSAR	Ka Band	RadarSAT, IIP/WSOA	One spacecraft in LEO	Infer sea ice thickness by measuring sea ice freeboard using INSAR with baseline 10 m and ground resolution of 500m.	Extending real aperture approach of WSOA to synthetic aperture; Lightweight (< 5kg/m^2), electronically scanned beams; sea-ice retrieval algorithms; rigid 10 m interferometer mast , precision metrology for antenna and mast
	Sea Ice Thickness Lidar	Vis/NIR	THOR (Thickness from Offbeam Returns) concept developed for cloud thickness determination	One spacecraft in LEO	Measure sea ice thickness using a lidar profiler by detection of water/ice interface in the 450-550 nm range.	Capability to overcome hurdles associated with interference/losses caused by scatter at the ice surface; wide angle telecentric telescope
	Land/Ice Topography Lidar	1064nm	SLA, MOLA, IceSAT/GLAS	One spacecraft in LEO	Determine ice surface topography and infer sea ice thickness by measuring sea ice freeboard using a laser altimeter.	Dual wavelength (1064nm and 532 nm - latter needed for cloud and aerosol correction), diode-pumped Nd:YAG laser transmitter with pulse width 4ns, PRF 100-200 Hz, pulse energy 10-20 mJ; efficient dissipation of multi kW heat loads on orbit; 1m diameter telescope optics; pointing knowledge to better than 1"
	Bistatic Interferometric Radar	VHF	New Development	One spacecraft in LEO	Provide direct measurement of sea ice thickness with precision of 20 cm, horizontal resolution of < 500 m with 300-500 km swath.	Cylindrical reflector with dual polarization, dual band array feed at VHF, combined with Ku band phased array feed; conformal dual-pol and dual-band VHF array feed with low mass; algorithm development for se ice thickness retrieval that overcome bandwidth limitation allocated for space instruments at VHF
	Radar	VHF	New Development	Mounted on Rover	Determine sea ice thickness and snow cover by electromagnetic induction and acoustics deployed on a long range surface rover. Data support spaceborne passive microwave and radar sea ice observations.	Capability to autonomously perform transect of Arctic ocean sea ice for distances of at least 1000 km, monitor location within 1km horizontally and 10 cm vertically, acquire ice thickness data of 5 cm or 2% accuracy and communicate results back to the continent.

2.5 Earth Surface & Interior

Table 8 shows a summary of science requirements for the Earth Surface & Interior theme provided by the cognizant ESE program scientist at NASA HQ.

Based on the science requirements presented in Table 8, a total of 16 measurement scenarios were discussed and validated at the workshop for this theme. These detailed scenarios can be found in ESTIPS by searching the "Science Drivers" -> "Earth Surface & Interior" Theme. A summary of the technology options and corresponding needed capabilities to meet the science requirements for this theme appears in Table 9.

Land Surface Topography & Surface Deformation There are a variety of technology options for measuring the land surface topography and surface deformation. Interferometric SAR in the X-band and L band on LEO, MEO, and GEO platforms are prominent options and have heritage from the proven past missions such as SRTM, AIRSAR, and SIR-C. The scenarios range from the use of one spacecraft in LEO to constellation of spacecrafts in LEO, MEO and GEO. Lightweight deployable antennas are among top requirements. The mass density requirement scales as < 6 kg/m^2 for LEO to <1-2 kg/m^2 for MEO and GEO platforms. The size of the needed antenna ranges from ~15 m^2 for LEO to ~ 400 m^2 for MEO and > 700 m^2 for GEO. Antenna flatness of λ/20 is required. Radiation shielding requirement is ~ 100 krad-1 Mrad for the LEO option and >1-10Mrad for the MEO and GEO options. Onbaord storage of 2-10 Gb and downlink in excess of 1 Gb/s are needed for the GEO option.

Another option is the use of airborne interferometric SAR in L-band, possibly mounted on a UAV. In this scenario, stability of the baseline within 5-10m tube is required.

Laser altimetry based on the heritage of MOLA and ICESAT/GLAS is another option. A variety of laser options could be used in this scenario. The requirements are high wallplug efficiency, narrow laser pulse width laser transmitters, array detectors with QE> 15%, narrow bandwidth filters, meter class telescope optics, and efficient dissipation of multi-kW heat loads on orbit.

Enhanced terrestrial networks of GPS receivers, laser ranging networks and VLBI networks are among other options.

Earth Surface Chemistry & Composition Measurement of Earth surface chemistry and composition can be achieved via hyperspectral imagers in greater than 220 bands in the 0.4-2.5 micron range. Requirements are low scatter, low polarization optics, low power and mass cooling systems, data compression techniques and high speed communication for data rates in excess of 1Gbps.

Earth Gravity Field There are a couple of competing scenarios for measurement of the Earth's gravity field. These are the laser interferometry technique based on the heritage of GRACE and the quantum gravity gradiometer technique (new development). In the case of the laser interferometry technique, single mode lasers with power 10-30mW, natural frequency noise < 100 MHz over 100 second sampling time, laser frequency stabilization system with stability of 10^{-15} rms over 100 seconds, and gravitation reference sensor with a test mass isolated to < 10^{-15} rms over 100 seconds are required. In addition, spacecraft position with respect to the test mass with accuracy of 1nm over 100 seconds is needed.

For the quantum gravity gradiometer scenario, compact laser sources capable of providing at least 1 W, with line width < 500 kHz at wavelengths corresponding to cesium and rubidium atom transition, and compact source of high flux atoms (> 10^{10}/s) with transverse temperature < 3 micro-Kelvin, in addition to compact beam shaping and beam delivery systems are required.

Earth Magnetic Field Measurement of Earth's magnetic filed and its gradient can be achieved via constellation of magnetometers in stratospheric altitudes. In this scenario, magnetometers of mass <5kg, and balloons with > 1 year lifetime with advanced trajectory control are needed.

More detailed technology requirements can be found in chapter 3 of this report.

Table 7: Summary of Earth Surface & Interior Science Theme Requirements

Science Requirement	Description	Measurement Requirements	Horizontal Resolution	Revisit Rate	Coverage	Accuracy
Land Surface Topography	Accurate land surface topography is fundamental for achieving a thorough understanding of the solid Earth, how it is changing and the consequences for life on Earth (e.g. earthquakes, volcanic eruptions, sea-level change, floods, etc.)	Measure land surface topography.	< 5m	every 3-5 years	global	< 1 m
Land Surface Topography	Accurate land surface topography is fundamental for achieving a thorough understanding of the solid Earth, how it is changing and the consequences for life on Earth (e.g. earthquakes, volcanic eruptions, sea-level change, floods, etc.)	Measure surface topography below vegetation	< 10m (1m optimal)	repetitive mapping as needed	global	< 1 m
Surface deformation and stress	Measure the deformation and stress accumulation in the Earth's crust before, during, and after seismic events to understand landscape-forming processes. These measurements will also lay the basis for assessment and prediction of geological hazards such as earthquakes and volcanic eruptions.	Measure land surface deformation (strain)	< 50m (1m optimal)	10-30 days (optimal is continuous)	global	precision 10^-6 (optimal 10^-9)
Earth Surface Compositions & Chemistry	Resolve the surface attributes and expression of many of the process related to natural and human-induced landscape change, volcanism, tectonics, and ice dynamics. The near-surface materials and their properties often determine a region's susceptibility to natural hazards such as earthquakes, wild fires and volcanic activity.	Measure surface reflectance and emittance for geomorphic feature mapping; stratigraphy, structure and surface dynamics	20-50 m (1m optimal)	One-time baseline mapping and repeated as necessary	global	NA
Terrestrial reference frame	Measure the Earth's center of mass to translate raw altimetry measurements (such as ocean surface height) into useful data and, eventually, enable mapping global water mass distribution, ocean bottom pressure, and total ocean transport.	Determine displacement of reference frame with respect to Earth's center of mass.	5000 km (2000 km optimal)	daily to weekly (optimal is continuous observation)	global	precision 2-5mm (1mm optimal)
Terrestrial reference frame	Measure the Earth's center of mass to translate raw altimetry measurements (such as ocean surface height) into useful data and, eventually, enable mapping global water mass distribution, ocean bottom pressure, and total ocean transport.	Determine Earth rotation relative to inertial space for Geodetic reference frame components of polar motion and length of day.	5000 km or better	daily to weekly (optimal is continuous observation)	global	precision 1cm (1mm optimal)
Terrestrial reference frame	Measure the Earth's center of mass to translate raw altimetry measurements (such as ocean surface height) into useful data and, eventually, enable mapping global water mass distribution, ocean bottom pressure, and total ocean transport.	Determine geodetic reference frame components of site positioning and velocity and polar motion.	1000-2000 km (100-1000 km optimal)	daily to weekly (optimal is continuous observation)	global	precision 1 cm or better (1mm optimal)

Table 7 (continued)

Science Requirement	Description	Measurement Requirements	Horizontal Resolution	Revisit Rate	Coverage	Accuracy
Earth gravity field	Measure the Earth's gravity field to translate raw altimetry measurements (such as ocean surface height) into useful data and, eventually, enable mapping global water mass distribution, ocean bottom pressure, and total ocean transport.	Map the Earth gravitational field (and its variation with time) with high precision. For the static gravity, optimal measurement is that of gravity gradient tensor.	<100km (50 km optimal)	Monthly temporal resolution (optimal is continuous observations)	global	< 2 cm geoid error
Motions of the Earth's interior	Changes in the Earth interior induce significant changes in the shape, rotation and wobbling motion of the Earth. Knowledge of these changes is essential for a variety of applications such as establishing the reference frame for precision geodesy, GPS satellite navigation, and ocean altimetry as well as for understanding the dynamics of the Earth's interior.	Knowledge of the Earth's gravity field, magnetic field, and rotation is needed to probe the Earth's interior. See the measurement requirements for these parameters.	NA	NA	global	NA
Earth's Magnetic Field	Knowledge of the Earth's magnetic filed provides one of three space-based techniques to probe the Earth's interior (the other two are Earth gravity and rotation).	Map Earth's magnetic field with high accuracy which is important for interannual secular variation measurements.	NA	monthly solution (optimal goal is solution from several spacecrafts with mixed inclinations and altitudes)	global	vector field to 1 nanoTesla; magnetic gradient tensor to 0.1 picoTesla/m @ 10Hz or better

Table 8: Summary of Earth Surface & Interior Theme Measurement Scenarios

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
Earth Gravity Field	Quantum Gravity Gradiometer	NA	New Development	Two spacecrafts in LEO	Observe the geoid to 100 km resolution (50 km goal) each month with 1 cm geoid error.	Compact (< 1000 cm^3) laser sources capable of providing at least 1 W, with line width < 500 KHz, at wavelengths corresponding to cesium and rubidium atom transition; compact (< 0.25 liter) source of high flux (> 10^10/s) atoms with transverse temperature < 3 micro-kelvin; compact beam shaping and beam delivery systems
	Laser Interferometer	IR	GRACE	Two spacecrafts in LEO	Observe the geoid to 100 resolution (50 km goal) each month with 1cm geoid error.	Single mode laser with power 10-30 mW; natural frequency noise < 100 MHz over 100 second sampling time; laser frequency stabilization system with stability of 1e-15 rms over 100 seconds; gravitational reference sensor with a test mass isolated to < 1e-15 rms over 100 seconds; spacecraft position with respect to the test mass with accuracy of 1 nm rms over 100 seconds
Earth Magnetic Field	Magnetometer	NA	NASA ULDB, StratoSail TCS	Constellation of stratospheric altitude balloons	Measure Earth's magnetic field and its gradient using an array of magnetometers positioned along a long tether and separated vertically by 2 km at 35 km altitude.	Magnetometer mass < 5 kg; balloon with > 1 year lifetime; advanced balloon trajectory control
Earth Surface Chemistry & Deformation	Hyperspectral Imager	> 220 bands, 0.4-2.5 micron	Landsat TM/ETM, AVIRIS, Terra/ASTER, EO-1/Hyperion	One spacecraft in LEO	Measure Earth surface composition, land cover and use, and biomass with 30-m spatial resolution, and 100 km swath. (This option is distinct from hyperspectral sensor for ocean color because of differences in dynamic range, polarization requirements, and UV bands.	Low scatter (<1%), low polarization (<2%) optics; spectrometers better than F/2; low power & mass cooling systems; data compression techniques and high speed communications (1Gbps data rate)
Land Surface Topography & Surface Deformation	Laser Altimeter	Vis/IR/NIR	Airborne IIP Microlaser Altimeter, ICESat/GLAS, MOLA, or LVIS	One spacecraft in LEO	Map surface elevation, vegetation height and vertical structure, river stage height and ice topography.	Multiple Laser Options; e.g. 532 nm Laser pulse width < 1ns and wallplug efficiency > 3%; array detector with single photon sensitivity and subnanosecond rise time, < 5 n; detector QE > 15%; narrow bandwidth filters; 1m diameter telescope optics; pointing knowledge better than 1"; efficient dissipation of multi-kW heat loads on orbit
	Interferometric SAR	X band	SIRC-C/X-SAR, SRTM	One spacecraft in LEO	Measure land surface topography with 10 m ground resolution and 4m vertical accuracy using a 100 m interferometric baseline.	Rigid fold-up or deployable membrane antenna of size ~ 15 m x 1m and flatness of lambda/20 and < 6 kg/m^2 areal density; small stow volume; high stiffness and thermally stable booms with < 2kg/m mass density; phase stable antenna and receivers (< 1deg)
	Interferometric SAR	L band	SIRC-C, AIRSAR/TOPSAR, SRTM, LightSAR	Two or more spacecrafts in sun-synchronous LEO	Measure land surface topography and deformation with 6mm/year 3D displacement rate accuracy, and 8-day repeat.	Lightweight, deployable antenna of size ~ 3m x 15m of < 6kg/m^2 areal density and flatness of lamda/20; radiation shielding > 100 Krad-1 Mrad; pointing knowledge of 0.05 deg
	Interferometric SAR	L band	SIRC-C, AIRSAR/TOPSAR, SRTM, LightSAR	Constellation of spacecrafts in MEO	Measure land surface topography and deformation with improved temporal coverage and accessibility relative to LEO, 2mm/year 3D displacement rate accuracy, 1-2 day repeat.	Lightweight, deployable antenna of size ~ 40m x 10m of < 2kg/m^2 areal density and flatness of lamda/20; high efficiency, distributed, rad-hard and low profile radar electronics and improved metrology and calibration for array; radiation shielding > 10 Mrad; pointing knowledge of 0.01 deg; onboard storage 2-10 GB, downlink 1GB/s
	Interferometric SAR	L band	SIRC-C, AIRSAR/TOPSAR, SRTM, LightSAR	Constellation of spacecrafts in GEO	Measure land surface topography and deformation with near continuous temporal coverage and accessibility relative to MEO, 1 mm/year 3D displacement rate accuracy, 12 hour repeat.	Lightweight, deployable antenna size > 700 m^2 and flatness of lambda/20 and and mass density < 1-2 kg/m^2; high efficiency, distributed, rad-hard and low profile radar electronics and improved metrology and calibration for array; radiation shielding > 10Mrad; onboard storage 2-10 GB; downlink 1 GB/s

Table 8 (continued)

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
	Airborne Interferometric SAR	L band	SIRC-C, AIRSAR/TOPSAR, SRTM, LightSAR	Sensor mounted on UAV	Measure land surface topography and deformation with improved regional coverage, accuracy and temporal resolution.	Phased array antenna (~2m x 0.5m), antenna mass density < 6 kg/m^2 and flatness lambda/20; data storage 400 GB; stability of baseline within a 5-10 m tube
	Terrestrial networks of GPS receivers	GPS L1 and L2	SCIGN, International GPS service	Terrestrial network	Advanced global navigation satellite system (GNSS) for use on the ground, data used to estimate earthquake potential, identify active blind thrust faults, and measure local variation in strain rate. Also used to measure terrestrial reference frame components of position and velocity.	Ability to perform kinematic positioning to < 5cm (1 cm goal). For static positioning, daily precision of < 0.5 mm (horizontal component) and < 1mm (vertical), approximately 5 x improvement over state of art
	Laser ranging network	NA	International laser ranging service	Terrestrial network	Measure displacement of reference frame with respect to Earth's center of mass using Satellite Laser Ranging (SLR) network.	Totally automated and eyesafe operation, high resolution ranging (1mm precision), low energy microlasers (130mJ/pulse) at high repetition rates (2 KHz), horizontal spacing ~ 5000 km (2000 km optimal)
	VLBI network	NA	International VLBI service	Terrestrial network	Uses VLBI to determine Earth rotation relative to inertial space for Geodetic reference frame components of polar motion and length of day.	Current measurements available at 5-20mm. Capability at mm level needed to answer key science questions.

2.5 Water & Energy Cycle

Table 9 shows a summary of science requirements for the water and energy cycle theme provided by the cognizant ESE program scientist at NASA HQ.

Based on the science requirements presented in Table 9, a total of 32 measurement scenarios were discussed and validated at the workshop for this theme. These detailed scenarios can be found in ESTIPS by searching the "Science Drivers" -> "Water & Energy Cycle" theme. A summary of the technology options and corresponding needed capabilities to meet the requirements for this theme appears in Table 10.

Soil Moisture Measurements of soil moisture can be accomplished via a variety of options from LEO. These include the 2D synthetic thinned aperture radiometer (STAR), large real aperture antenna radiometer and scatterometer, and the very large real aperture mesh antenna radiometer in the L band. Effective aperture of 10-20 m as well as radiometer stability to ~0.1K is needed for the STAR option. For the real aperture option, rotating (~5m and ~25m, respectively, for the large and the very large options) deployable antennas with high reflectivity (>0.99) are needed. Ability to control and stabilize large rotating mesh antennas is crucial.

The deep soil moisture SAR in UHF & VHF band is another possibility. Aperture size of ~ 30m x 11m at VHF, 30m x 3m at UHF, and lightweight deployable structures and reflectors are needed for this scenario.

A beam synthesis radiometer in L band operated from LEO provides another option for soil moisture measurement. Deployable structures incorporating tensioned rigid panels or membranes, 15-20 m booms with <0.1 kg/m mass density and maintaining better than λ/20 RMS surface distortion are among the requirements for this scenario.

Atmospheric Water Vapor The atmospheric water vapor can be measured via a wide range of technology options. A microwave sounder option in GEO requires antenna array efficiency > 95%, MMIC radiometers with noise figure < 4db, and 10% bandwidth. The platform must be capable of supporting 500-1000W for the instrument.

The RF occultation radiometer at LEO based on the heritage of MLS is another option. For this scenario, capability for onboard processing of huge data volume, navigation accuracy to 20 cm, and pointing accuracy to 1mrad is required.

An IR DIAL sensor at LEO will require efficient laser transmitter systems with energy > 1J, narrow linewidth, and >8% overall power efficiency. A geosynchronous IR Fourier Transform Spectrometer will require thermally stable (~77-300K) lightweight optics and mount material, long lifetime space qualified cryocoolers (or background limited uncooled detectors), and high rate, low power DSP electronics and data compression techniques.

Dropsondes from constellation of stratospheric long duration balloons provide another option. In this scenario, mass reduction of dropsondes by a factor of 4-5 is needed to allow 1000s of dropsondes on a single platform.

Global Precipitation Global precipitation measurements can be achieved via dual/tri frequency precipitation radar in the Ku, Ka, mm wave band based on the heritage of TRMM or the proposed GPM precipitation radars from LEO. Lightweight (< 4 kg/m^2) inflatable deployable antennas of size ~ 6 m x 6m are needed. Optical communication is an enhancing capability for this scenario.

Doppler rain profiling radar at Ka band from GEO is another option. Lightweight, deployable membrane spherical antenna > 30 m diameter, and radiation hardness for GEO orbit along with 0.25deg pointing accuracy are needed.

River Stage Height & Discharge Rate For the measurement of river stage height and discharge rate, a wetland & river monitoring radar in the Ka band from LEO is a possibility. Deployable antenna with <2kg/m^2, 5m deployable phased array or reflector and 10m interferometeric mast are required. Laser altimetry has also been suggested using a variety of lasers with high wallplug efficiency and detectors with > 15% QE.

Snow Cover, Accumulation, & Water Content The snow cover, accumulation, and equivalent water content can be measured using a variety of active and passive remote sensing techniques in the microwave and RF band. These range from the use of cold land scatterometer in Ku band, Ku plus L band snow polarimeteric InSAR, real aperture conical scanning microwave radiometer in the K-Ka band, and 1-2D synthetic thinned aperture radiometer (STAR) from LEO. Requirements are lightweight (< 5kg/m^2) , deployable, Ku band array antenna with phase stability to <0.05 deg and > 2kW transmit power, 10-50 m interferometric mast, and calibration/metrology techniques for accurate baseline knowledge. Pointing control and attitude knowledge to 0.5 deg and 0.1", respectively, are also required. These concepts are currently under study supported by ESTO.

Freeze-Thaw Transition The freeze-thaw transition can be measured via a cold land dual frequency SAR. Requirements are deployable mesh or inflatable antennas of size ~ 10-15m x 2-3m with mass density < 2 kg/m^2.

More detailed technology requirements can be found in chapter 3 of this report.

Table 9: Summary of Water & Energy Cycle Science Theme Requirements

Science Requirement	Description	Measurement Requirements	Horizontal Resolution	Vertical Resolution	Revisit Rate	Coverage	Accuracy
River stage height	Measure river stage height to study regional hydrological impacts of climate change, such as floods, droughts, and water availability.	measure stage height for major world rivers & inland water bodies	10m	2cm	1/day	global	1cm
River discharge rate	Measure river discharge rate to study regional hydrological impacts of climate change, such as floods, droughts, and water availability.	measure discharge rate for major world rivers & inland water bodies	10m	2cm	1/day	global	10-15% of the flow volume
Freeze-thaw transition	Conduct large-scale observations of the transition between frozen and thawed soil conditions to develop a quantitative understanding of hydrologic processes. These processes control river flow, available water resources, surface temperature, and the growth of terrestrial ecosystems.	Measure freeze-thaw transition in all cloud and vegetation conditions.	10-250 m	2cm	2/day	global	10-15% error rate
Snow cover and accumulation	Conduct large-scale observations of snow accumulation and snowpack to develop a quantitative understanding of hydrologic processes. These processes control river flow, available water resources, surface temperature, and the growth of terrestrial ecosystems.	measure snow extent, snow melt onset, snow wetnessand duration, snow water equivalent and surface-freeze thaw with and without snow cover. Need ultra-wide 2000km swath	500m-1km	N/A	2/day	global	10%
Soil moisture	Measure soil moisture, which is a key factor in the global water and energy cycles, climate variations, the ability of ecosystems to support life, large-scale hydrology, and weather prediction.	measure top soil moisture	1km	3-4cm top soil	1/day	global	3%
Soil moisture	Measure soil moisture, which is a key factor in the global water and energy cycles, climate variations, the ability of ecosystems to support life, large-scale hydrology, and weather prediction.	measure root zone soil moisture	1km	50cm deep	1/day	global	4%

Table 10: Summary of Water & Energy Cycle Theme Measurement Scenarios

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
Soil Moisture	2D Synthetic Thinned Aperture Radiometer (STAR)	L Band	GSFC ESTAR airborne radiometer	One spacecraft in LEO	Measure soil moisture using a STAR radiometer with spatial resolution of 10km, 950 km swath, 2-3 day revisit time.	1.4 GHz STAR radiometer with 20 MHz bandwidth and dual polarization; effective aperture of 10-20m; radiometer receiver stability ~0.1K over several days; low power (< 0.2 W) per receiver element
	Large Real Aperture Antenna Radiometer and Scatterometer	L Band	Development in NASA IIP and Aquarius	One spacecraft in LEO	Measure soil moisture with 10 km spatial resolution using a rotating real aperture radiometer with mesh antenna with 900 km swath and global coverage every 3 days.	Rotating (< 5rm), size ~25m diameter deployable antenna with beam efficiency > 92% and surface reflectivity > 0.99; radiometer stability of 0.1 K over 2-5 days
	Very Large Real Aperture Mesh Antenna Radiometer	L Band	IIP development, Aquarius Mission	One spacecraft in LEO	Measure surface (< 5cm) soil moisture with 1-10 km spatial resolution with 900 km swath, global coverage every 3 days.	Rotating 25m diameter deployable antenna with mesh or inflatable design and high reflectivity > 0.995; ability to control and stabilize large rotating mesh antenna
	Deep Soil Moisture SAR	UHF & VHF	SIR-C, AIRSAR	One spacecraft in LEO	Measure soil moisture at root zone depth (1-5m below surface) to 4% accuracy (absolute) and 1% accuracy for relative change, with 7-10 day repeat observation and 400km swath.	Aperture size ~ 30m x 11m at VHF, 30mx 3m at UHF; lightweight deployable structures and reflectors (~500-600 kg reflector, feed, boom); pointing knowledge and control 0.1 deg
	Beam Synthesis Radiometer	L Band	ESMR, PBMR (airborne)	One spacecraft in LEO	Measure surface (< 5cm) soil moisture with 10-20 km spatial resolution with 900 km swath, global coverage every 3 days.	Deployable structures incorporating tensioned rigid panels or membranes; 15-20m booms with < 0.1kg/m; maintain better than 1/20 RMS surface distortion requirement
Atmospheric Water Vapor	Microwave Sounder	50 Hz, 183 Hz	Aqua AMSU & HSB, NPP ATMS	One spacecraft in GEO	Make continuous (every 15 min) measurements of atmospheric temperature, water vapor, and rainfall using a microwave radiometric sounder.	Antenna array efficiency > 95%; 50 and 183 GHz MMIC radiometers with noise figure < 4 dB, 10% bandwidth and power , 0.3 W; platform capable of supplying 500-1000W for the instrument
	RF Occultation Radiometer	Microwave, mm Band	MLS	Two spacecrafts in LEO	Measure profiles of water vapor and temperature by a rising or setting pair of spacecrafts using the atmospheric occultation technique with < 1km vertical resolution and 200km horizontal resolution.	Ability for onboard processing of huge data volume; navigation accuracy to 20 cm; pointing accuracy to 1mrad
	IR Differential Absorption Lidar (DIAL)	IR	LASE and other ground based or airborne measurements	One spacecraft in LEO	Measure atmospheric temperature and water vapor using an IR DIAL.	Small, efficient DIAL system with energy > 1J, pulse at 10Hz, narrow linewidth (99.5%), pumping by conductively cooled diode lasers and > 8% overall power efficiency

Table 10 (continued)

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
	Geosynchronous IR Fourier Transform Spectrometer	IR	AIRS, NMP EO-3/GIFTS	One spacecraft in GEO	Measure atmospheric temperature and water vapor with spatial resolution of 4 km, vertical profile resolution of 2 km, and spectral resolution of 0.3 cm-1 or greater.	Thermally stable (~77-300k) optics and mount material lighter than aluminum; long lifetime space qualified 77 cryocoolers and/or background limited uncooled detectors; long lifetime space qualified stabilize (dnu/nu < 5E-7) metrology lasers; high rate and low power DSP electronics and data compression techniques
	Dropsonde	NA	NCAR GPS dropsonde	Constellation of stratospheric long-duration balloons	Measure atmospheric temperature, water vapor, ozone, and winds from stratosphere to surface with an accuracy of 1% at > 20km using a meteorological dropsonde deployed from long duration balloons.	Mass reduction of dropsonde (including capability for ozone measurement) by a factor of 4-5 to allow 1000s on a single platform; long duration balloons with trajectory control system
Global Precipitation	Dual/Tri Frequency Precipitation Radar	ku, Ka, mm Band	TRMM, GPM Precipitation Radar	One spacecraft in polar LEO	Measure the horizontal and vertical structure of rainfall and its microphysical elements as well as rainfall rate. Dual frequency required to unambiguously determine precipitation water content profile. Third frequency (mm band) measures cloud patterns.	Lightweight (< 4 kg/m^2) inflatable, deployable antenna of size ~ 6 m x 6 m; 14/35 GHz dual frequency radar electronics; 150-250W equivalent output power at each frequency; optical communication is enhancing
	Doppler Rain Profiling Radar	Ka Band	GPM Precipitation Radar	One spacecraft in GEO	Measure rainfall intensity and Doppler wind associated with hurricanes with a horizontal resolution of 12 km and vertical resolution of 300 m. The data is also valuable for more accurate prediction of hurricane tracks and severity.	Lightweight, deployable membrane spherical antenna > 30 m diameter; radiation hardness for GEO orbit; 0.025 deg pointing accuracy
River Stage Height & Discharge Rate	Wetland & River Monitoring Radar	Ka Band	SRTM, WSOA, AIRSAR	One spacecraft in LEO	Measure water storage in wetlands, lakes, and river discharge with a few centimeter height accuracy and few cm/s velocity accuracy with 50-100km swath.	Deployable antenna with < 2kg/m^2 ; 5m deployable phased array or reflector; 10m interferometric mast
	Laser Altimeter	Vis/IR/NIR	Airborne IIP Microlaser Altimeter, ICESat/GLAS, MOLA, or LVIS	One spacecraft in LEO	Map surface elevation, vegetation height and vertical structure, river stage height and ice topography.	Multiple Laser Options; e.g. 532 nm Laser pulse width < 1ns and wallplug efficiency > 3%; array detector with single photon sensitivity and subnanosecond rise time, < 5 n; detector QE > 15%; narrow bandwidth filters
Snow Cover, Accumulation, & Water Content	Cold Land Scatterometer	Ku Band	NSCAT, QuikSCAT	One spacecraft in LEO	Measure snow accumulation and snowmelt processes with1 km spatial resolution, and high temporal resolution (twice daily) over global scale (> 35 deg latitude) and 2000 km swath.	Real aperture (RAS) or Doppler beam sharpening (DBSS) scatterometer; > 3 m diameter deployable mesh antenna with > 80% aperture efficiency; scanning elliptical antenna; 1kW transmit power
	Ku Band (or Ku plus L Band) Snow (Polarimetric) INSAR	Ku/L Band	SIR-C/SRTM, ERS-1/2, AirSAR, GeoSAR	One spacecraft in LEO	Measure snow water equivalent (SWE) to 3cm height accuracy for SWE > 0.3m or 10% height accuracy for SWE <0.3m and 10% snow wetness accuracy, with 3-day revisit, > 500 km swath and < 100m spatial resolution.	Lightweight deployable antennas (< 5 kg/m^2); ku-band array antenna with phase stability to < 0.05 deg; > 2kW transmit power; 10-50m interferometric mast; calibration/metrology for accurate baseline knowledge; 0.5 deg pointing control; 0.1" attitude knowledge
	Real Aperture Conical Scanning Microwave Radiometer	K, Ka Band	SMMR, SSM/I, AMSR, CMIS	One spacecraft in LEO	Measure snow water equivalent (SWE) with 5km horizontal resolution. Passive system supports active radar system.	> 6m aperture conical scanning reflector (10-60rpm), stowable/deployable; 200um RMS surface figure

Table 10 (continued)

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
	1D or 2D Synthetic Thinned Aperture Radiometer (STAR)	K, Ka Band	SMOS, STAR-Light, ESTAR, 2D ESTAR, HUT-STAR, MIRAS	One spacecraft in LEO	Measure snow water equivalent (SWE) with 5km horizontal resolution. Passive system supports active radar system.	Cylindrical parabolic reflector > 6m x 12 m for 1D concept; large, 2D STAR structure (e.g. Y-shaped with > 3m arms) supporting > 200 microwave receiver elements per arm for 2D concept
	Radar	VHF	New Development	Mounted on Rover	Determine sea ice thickness and snow cover by electromagnetic induction and acoustics deployed on a long range surface rover. Data support spaceborne passive microwave and radar sea ice observations.	Capability to autonomously perform transect of Arctic ocean sea ice for distances of at least 1000 km, monitor location within 1km horizontally and 10 cm vertically, acquire ice thickness data of 5 cm or 2% accuracy and communicate results back to the continent.
Freeze-Thaw Transition	Cold Land Dual Frequency SAR	L Band	Seasat SAR, SIR-C/X-SAR, LightSAR, AIRSAR	One spacecraft in polar sun-synchronous orbit	Measure freeze-thaw transition at > 40 deg northern latitudes with 1km spatial resolution, 700 km swath, 2-day repeat.	Deployable mesh or inflatable antennas, size ~ 10-15m x 2-3m, areal density < 2kg/m^2, high efficiency (> 60%), low mass (<50g) T/R modules; pointing knowledge and control 0.5 degrees; data rate ~ 18Mbps

2.6 Weather

Table 11 shows a summary of the science requirements in the weather theme provided by the cognizant ESE program scientist at NASA HQ.

Based on the science requirements presented in Table 11, a total of 39 measurement scenarios were discussed and validated for this theme at the workshop. These detailed scenarios can be found in ESTIPS by searching the “Science Drivers” -> “Weather” theme. A summary of the technology options and corresponding needed capabilities to meet the requirements for this theme appears in Table 12.

Atmospheric Properties Atmospheric water vapor and temperature can be measured via a variety of techniques. A microwave sounder in GEO can make continuous measurements of atmospheric properties and rainfall. Among the requirements are antenna efficiency greater than 95%, MMIC radiometers with noise figure < 4dB and 10% bandwidth while platform must be capable of supplying 500-1000W for the instrument.

Another option is the use of a RF occultation radiometer from LEO based on the heritage of MLS. In this scenario, capability for onboard processing of huge data volumes, navigation accuracy to 20 cm, and pointing accuracy to 1mrad are required.

A UV temperature lidar in LEO measures atmospheric temperature profiles using a direct detection lidar. This scenario requires diode pumped, conduction cooled solid state laser transmitters at 1 micron with energy > 1J, wall-plug efficiency > 6% and detector QE > 40%.

IR differential absorption lidar (DIAL) option in LEO measures atmospheric water vapor and temperature. The scenario requires efficient DIAL systems with energy > 1J and narrow line-width.

Another option is a GEO IR Fourier Transform Spectrometer based on the heritage of AIRS, and work under development for NMP EO-3/GIFTS. Among the requirements are thermally stable (~77-300K) optics and mount material lighter than aluminum, long-lifetime space qualifiers (or uncooled detectors), and high rate and low power DSP electronics and data compression techniques.

Use of meteorological dropsondes on a constellation of stratospheric long duration balloons is another option. For this scenario, reduction of dropsondes mass by a factor of 4-5 is required to allow thousands of dropsondes on a single platform.

Ocean Surface Winds The ocean surface winds can be measured via real aperture scatterometer in the Ku band based on the heritage of ADEOS II Seawinds on a LEO or MEO platform. Reduction of mass, power, and volume of instrument by a factor of 2-3 is needed to allow easier accommodation on operational weather satellites. The MEO orbit requires ~ 3-10m antenna aperture, high power transmitter and rad-hard electronics.

Global Precipitation Global precipitation can be measured via dual or tri-frequency precipitation radar from LEO in the Ku, Ka, and mm bands. Lightweight (<4kg/m^2) inflatable deployable antenna of size ~ 6m x 6m are needed.

Another option is the use of Doppler rain profiling radar from GEO which requires lightweight, deployable membrane spherical antenna > 30 m diameter, 0.025 deg pointing accuracy, and radiation hardness for GEO orbit.

Lightning Rate Monitoring the lightning rate can be achieved via a GEO lightning imager in the UV band. Advances in high speed (~1 frame/ms), 2D mega pixel FPAs and capability to rapidly cover many fields of view are required.

Tropospheric Winds Tropospheric winds can be measured via a variety of scenarios including the use of a coherent wind lidar, direct detection Doppler wind lidar, and the hybrid Doppler wind lidar.

The coherent Doppler wind lidar measures tropospheric winds by illuminating the atmosphere with a laser signal and detecting returns from aerosols. This technique works best in the aerosol rich 0-3km altitude range and against cloud backgrounds. It requires 2-micron laser conductivity cooled transmitter, lightweight diffraction limited optics with ~ 0.75 aperture with conical scan capability.

The direct detection Doppler wind lidar measures tropospheric winds by illuminating the atmosphere with a laser signal and detecting returns from molecules and aerosols. The Doppler shifted returns are sent through a high resolution optical filter whose transmission is wavelength dependent. Intensity differences indicate frequency shifts related to wind velocity. Molecule returns will be best in the upper troposphere above 3km and aerosol returns are best below 3km. This technique offers coverage over the full tropospheric altitude range (0-20km) and requires diode pumped, conduction cooled solid state laser transmitter operating near 1 micron, and low mass ~1.5 m aperture optics telescope with conical scan capability.

Finally, the hybrid lidar approach combines both approaches and operates in the UV and mid-infrared to measure tropospheric winds with 1m/s, 3 deg accuracy. It covers the full tropospheric altitude range (0-20km). This scheme requires a combination of capabilities for direct and coherent detection wind lidars.

Storm Cell Properties Storm cell properties are best studied from UAV or balloon platforms using a variety of techniques such as the use of lidars (e.g. DIAL, Doppler wind), precipitation and cloud profiling radars, and high resolution interferometric sounders. The platform requires instruments of small volume, low mass and power with high speed signal processing and acquisition systems. Long duration airborne or balloon platforms are required for these scenarios.

Clouds & Aerosol Properties There are multiple techniques for the measurement of cloud and aerosol properties. A variety of lidars on a LEO or airborne platform can be utilized. In general, technology development to reduce mass, power, size and cost of the instruments are needed.

Another option is the use of multi-angle spectroradiometer or multi-spectral imaging spectroradiometer based on the heritage of MISR, and Terra & Aqua MODIS, respectively. Improved methods for radiometric calibration, high QE detectors and uncooled IR FPAs or IR detectors with modest cooling requirements are needed.

A cloud profiling radar in the mm band is another option. In this scenario, deployable mm-wave antenna (> 2m) are needed.

A submm/IR radiometer provides another option. Technology development of 1 THz oscillators to allow combination of submm and far IR sensors into a single instrument is needed.

Finally, aerosol polarimeter can measure aerosol properties in more than 12 bands in the visible and IR band. Technology development to reduce size, mass and power for the instrument is needed.

More detailed technology requirements can be found in chapter 3 of this report.

Table 11: Summary of Weather Science Theme Requirements

Science Requirement	Description	Measurement Requirements	Horizontal Resolution	Vertical Resolution	Revisit Rate	Coverage	Spectral Resolution	Accuracy
Storm cells properties	Measure the three-dimensional structure of atmospheric temperature, moisture, and wind around storm cells to determine the life cycle of mesoscale storms over land and relate that life cycle to atmospheric circulation and climate change.	measure meteorological properties around storms	1 km	500m	10 min	local	vis, IR, MW	0.5 deg K
Atmospheric temperature	Measure atmospheric temperature, which determines large-scale atmospheric flow, including weather.	measure atmospheric temperature under all weather conditions & presence of clouds	10km	<0.5km	2/day	global		<1K
Atmospheric water vapor	Measure atmospheric water vapor, which is the principal vehicle of atmospheric energy driving weather and precipitation. Water vapor is also a factor in the global water cycle and amplifies the greenhouse effect.	measure atmospheric water vapor	10km	<0.5km	2/day	global		10%
Global precipitation	Measure global precipitation, which is a principal indicator of the global water cycle rate and is an input for numerical weather forecasting. It is also important to relate global precipitation to climate change.	monitor rain fall	<25km	250m	~3 hrs	global coverage up to +/-75 latitude band		10%
Lightning rate	Measure the rate of lightning strokes to get information about thunderstorms, severe weather, and rainfall; relate climate change to weather systems.	measure lightning rate	10 km	N/A	Continuous staring	Hemisphere	Hydrogen-alpha	>90%
Tropospheric winds	Measure tropospheric winds as a prototype operational application to improve weather forecasting.	measure trop winds with 2-D vector component	100km	1km mid/upper trop, 250m in PBL	~6 hrs.	global	TBD	1-3 m/s
Ocean surface winds	Measure ocean surface winds to determine changes in ocean circulation, which could have a significant effect on climate due to the enormous amount of heat stored in the ocean. Ocean surface winds also provide a direct measure of storm tracks, strength, and life cycle. This measurement will help relate large-scale atmospheric circulation and climate change to severe weather systems.	measure wind vector field over both ocean and coastal areas; need 200 km single-pass swath	1km	N/A	2/day	global	MW	speed <2m/s;direction <20deg

Table 12: Summary of Weather Theme Measurement Scenarios

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
Atmospheric Water Vapor & Temperature	Microwave Sounder	50 Hz, 183 Hz	Aqua AMSU & HSB, NPP ATMS	One spacecraft in GEO	Make continuous (every 15 min) measurements of atmospheric temperature, water vapor, and rainfall using a microwave radiometric sounder.	Antenna array efficiency > 95%; 50 and 183 GHz MMIC radiometers with noise figure < 4 dB, 10% bandwidth and power , 0.3 W; platform capable of supplying 500-1000W for the instrument
	RF Occultation Radiometer	Microwave, mm Band	MLS	Two spacecrafts in LEO	Measure vertical profiles of water vapor and temperature and various atmospheric constituents by a rising or setting pair of spacecrafts using the atmospheric occultation technique with < 1km vertical resolution and 200km horizontal resolution.	Ability for onboard processing of huge data volume; navigation accuracy to 20 cm; pointing accuracy to 1mrad
	UV Temperature Lidar	UV	Ground based measurements (NDSC)	One spacecraft in LEO	Measure atmospheric temperature profile using a direct detection UV backscatter lidar.	Better temperature measurement accuracy than existing passive techniques (e.g. using AIRS); diode pumped, conduction cooled solid state laser transmitters at 1micron with energy 1J, wallplug efficiency > 6%; detector QE > 40%; low mass, large (> 1.5 diameter) optics with high damage threshold coating
	IR Differential Absorption Lidar (DIAL)	IR	LASE and other ground based or airborne measurements	One spacecraft in LEO	Measure atmospheric temperature and water vapor using an IR DIAL.	Small, efficient DIAL system with energy > 1J, pulse at 10Hz, narrow linewidth (99.5%), pumping by conductively cooled diode lasers and > 8% overall power efficiency
	Geosynchronous IR Fourier Transform Spectrometer	IR	HIS/GHIS, NAST-I, AIRS, NMP EO-3/GIFTS	One spacecraft in GEO	Measure atmospheric temperature and water vapor with spatial resolution of 4 km x 4km, vertical profile resolution of 2 km, and spectral resolution of 0.3 cm-1 or greater.	Thermally stable (~77-300k) optics and mount material lighter than aluminum; long lifetime space qualified 77 cryocoolers and/or background limited uncooled detectors; long lifetime space qualified stabilize (dnu/nu < 5E-7) metrology lasers; high rate and low power DSP electronics and data compression techniques
	Dropsonde	NA	NCAR GPS dropsonde	Constellation of stratospheric long-duration balloons	Measure atmospheric temperature, water vapor, ozone, and winds from stratosphere to surface with an accuracy of 1% at > 20km using a meteorological dropsonde deployed from long duration balloons.	Mass reduction of dropsonde (including capability for ozone measurement) by a factor of 4-5 to allow 1000s on a single platform; long duration balloons with trajectory control system
Global Precipitation	Dual/Tri Frequency Precipitation Radar	ku, Ka, mm Band	TRMM, GPM Precipitation Radar	One spacecraft in polar LEO	Measure the horizontal and vertical structure of rainfall and its microphysical elements as well as rainfall rate. Dual frequency required to unambiguously determine precipitation water content profile. Third frequency (mm band) measures cloud patterns.	Lightweight (< 4 kg/m^2) inflatable, deployable antenna of size ~ 6 m x 6 m; 14/35 GHz dual frequency radar electronics; 150-250W equivalent output power at each frequency; optical communication is enhancing
	Doppler Rain Profiling Radar	Ka Band	GPM Precipitation Radar	One spacecraft in GEO	Measure rainfall intensity and Doppler wind associated with hurricanes with a horizontal resolution of 12 km and vertical resolution of 300 m. The data is also valuable for more accurate prediction of hurricane tracks and severity.	Lightweight, deployable membrane spherical antenna > 30 m diameter; radiation hardness for GEO orbit; 0.025 deg pointing accuracy
Lightning Rate	Geosynchronous Lightning Imager	UV (hydrogen alpha)	TRMM LIS	One spacecraft in GEO	Measure lightning rate (time of event as well as its radiant energy and estimated location) even under bright, sunlit clouds.	Advances in high speed (~ 1 frame/ms) 2-D megapixel FPAs; wide angle, narrow bandpass (~1 Angstrom) hydrogen alpha filters; capability to rapidly cover many fields of view

Table 12 (continued)

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
Ocean Surface Winds	Real Aperture Scatterometer	Ku Band	ADEOS II Seawinds	One spacecraft in LEO or MEO	Measure ocean surface winds under all weather and cloud conditions with 2m/s wind speed and 20 deg wind direction accuracy.	Reduction of mass, power and volume of instrument by a factor of 2-3 to allow easier accommodation on operational weather satellites; low mass multiple beam or steerable antennas; MEO orbit requires ~3-10 m antenna aperture and > 50% efficiency T/R modules, high power transmitters > 1 kW, and rad-hard electronics
Tropospheric Winds	Coherent Doppler Wind Lidar	IR	Ground based or airborne (MACAWS, TODWL) measurements, SPARCLE	One spacecraft in LEO	Measure tropospheric winds with 2D vector component using the coherent wind lidar. This approach works best in the aerosol rich 0-3 km altitude range and against clouds, and offers excellent wind velocity accuracy.	2-micron laser conductivity-cooled transmitter with 2J/pulse at PRF 12 Hz; lightweight diffraction limited optics (0.75m aperture) with conical scan capability; pointing knowledge accuracy to +/- microrad
	Direct Detection Doppler Wind Lidar	UV and NIR	Ground based measurements, ZEPHYR	One spacecraft in LEO	Measure tropospheric winds with 2D vector component using the direct detection wind lidar. This technique offers coverage over the full tropospheric altitude range (0-20km).	Diode pumped, conduction cooled solid sate laser transmitter operating near 1 micron; 1 MHz frequency stability over 5 sec; laser energy of 1J and PRF 100 Hz and wallplug efficiency > 6-8%; efficient (> 40%) harmonic conversion to UV; high (> 40%) QE detectors; low mass ~1.5m aperture optics telescope, 50x diffraction limited performance; pointing knowledge accuracy ~30 microrad
	Hybrid Doppler Wind Lidar	IR to UV	LAWS/SPARCLE /ZEPHYR	Two spacecrafts in LEO	Measure tropospheric winds with 2D vector component using the hybrid Doppler wind lidar with 1m/s and 3 deg accuracy over the full tropospheric altitude range (0-20km).	Combination of capabilities required for direct and coherent direction wind lidars (above); lasers with ~1J power and 20-40 Hz PRF at 355nm and 2050 nm; high wavefront quality (1/10-wave or better with active surface figure controllability) optics
Storm Cell Properties	Lidar	UV to IR	Variety of airborne lidar or DIAL	Mounted on UAV or Balloons	Measure aerosols, water content, wind structure and other atmospheric properties around storm cells.	DIAL and Doppler wind lidars to cover the range of parameters being measured; long duration airborne or lighter than air platforms
	High Resolution Interferometric Sounder	IR	NAST-I (NPOES)	Mounted on UAV	Measure water vapor and temperature around storm cells with a Michelson interferometer at high temporal and spatial resolution.	Thermally stable (~77-300k) optics and mount material lighter than aluminum; low mass (0.5 kg) low power (< 4W) cryocoolers for focal plane detectors (~85K) or uncooled IR detectors; lightweight FTS mirror scan servo (tilt error < 2 microradians, velocity error < 1%, max optical depth difference +/- cm)
	Precipitation and Cloud Profiling UAV Radar	Ku, Ka Band	ER-2 Doppler Radar (EDOP) at X Band	Mounted on UAV	Measure precipitation and wind structure around storm cells using a Doppler radar on a long duration (> 24 hr) UAV platform.	Small system size (<0.6 cubic meter), low mass (< 100kg) and power (< 300W) with autonomous operation; compact, high speed signal processing and acquisition system
Clouds & Aerosol Properties	Variety of Lidars	UV/Vis/IR	LITE, CALIPSO, Airborne DIAL	One spacecraft in LEO; or Airborne Platforms	Measure stratospheric aerosol distribution and cloud properties with high spatial and vertical resolution in multi wavebands from UVI to IR using a variety of spaceborne lidars.	Technology to reduce mass, power, size, and cost of instrument; small laser transmitter system with wallplug efficiency > 10%; detector QE > 50%; stable, narrowband, tunable filters (10GHz full width half max, 90% transmittance)

Table 12 (continued)

Science Application	Sensor Technology Option	Sensor Waveband	Heritage	Measurement Platform	Measurement Scenario	Required Capabilities
	Multi-Angle Spectroradiometer	Vis/IR	MISR	One spacecraft in LEO	Provide multiple-angle coverage of the Earth with high spatial resolution with data on aerosol sampling, cloud properties and planetary radiation budget.	Technology to reduce mass and size by a factor of 3; improved angle-to-angle absolute radiometric calibration
	Multi-Spectral Imaging Spectroradiometer	Vis/IR	Terra & Aqua MODIS, NPOESS VIIRS	One spacecraft in LEO	Measure atmospheric aerosol, cloud droplet size and optical depth in 36 bands with a spatial resolution of 250m at nadir and swath width 2300km.	Improved method for radiometric calibration of IR bands in a pushbroom instrument; narrow bandwidth optical filters (0.2% of center wavelength); large format FPAs with improved noise properties, and high QE; uncooled IR FPAs or IR detectors with modest cooling requirements
	Aerosol Polarimeter	Vis/IR	Aerosol Polarimetry Sensor (APS), Pioneer Venus/CPP, Galileo Orbiter/PPR	One spacecraft in LEO	Measure aerosol properties in 12 bands using a multi-spectral, multi-angle polarimeter which provides data on optical depth, single scatter albedo, particle size and shape, and refractive index .	Technology development to reduce cost, size, mass, and power.
	Cloud Profiling Radar/Dual Frequency Radar	94 GHz; 94 & 140 GHz	Airborne Cloud Radar, CloudSast/CPR	One spacecraft in LEO	Measure cloud systems using a mm-wave radar with spatial resolution of 3.5 km and vertical resolution of 500m. Dual frequency option allows increased sensitivity to the thin cirrus clouds.	Technology to reduce mass, size, power; deployable mm-wave antenna (> 2m); optical communication is enhancing
	Sub-mm/Far IR Radiometer	Sub-mm/Far IR	Limb Sounding radiometers	One spacecraft in LEO	Measure cloud systems using a sub-mm wave radiometer in 8 bands.	Technology development of 1 THz oscillators to allow combination of submm and far IR sensors into a single instrument; deployable mm-wave antenna

3.1 Sensor Technologies

3.1.1 Active Optical: Laser/Lidar Technologies

Panel A reviewed technology requirements for active optical sensor systems. Although the panel was able to significantly update many of the scenarios, some remain in a low-fidelity state lacking in detailed quantitative requirements for technology development. Several of the scenarios proposed may seem impractical even if technically feasible, since the panel felt that certain of the concepts might be unable to deliver the measurement promised without irradiating the Earth at levels well in excess of regulatory eye-safety limits. These scenarios would benefit from a first-order system requirements assessment, with particular emphasis on the radiometric budget.

The following list identifies technology needs common to many of the active optical instrument concepts appearing in the ESTIPS database.

Transmitter Lasers

In general, active optical remote sensing systems from a space-borne platform place excessive demands on the transmitter laser performance. These requirements are difficult to meet within the constraints of current technology.

Common performance needs are for pulse energies in the range 0.5-2.0 J at pulse repetition frequencies (PRFs) up to 100 Hz, and up to 200 mJ at PRFs from 1-50 kHz, at wavelengths in the UV, visible, NIR, and shortwave MIR. Current flight heritage is limited to ~300 mJ at 50-Hz PRF. In addition, some applications call for tunable single frequency operation with linewidths of 500 kHz or better. Breakthroughs in materials and system architecture to extend wallplug efficiencies from current 6% state-of-the-art to 10% or better are *highly* desirable.

Phased array transmitter technologies would enable rapid, flexible beam steering while obviating the need for an associated mechanism. The phased array approach also offers graceful degradation of the transmitter.

Lifetime continues to be an issue with high power lasers, with 30,000 hours being the general requirement. Pump diode arrays are desired with average lifetime of 50,000-100,000 hours.

Detection and Processing

Significantly improved detector performance is required in many of the scenarios (currently quantum efficiencies can be as low as 2% for some photon counting schemes). Quantum efficiencies of order 30-50% in the visible/UV are needed for photon counting and analog mode devices with noise equivalent power (NEP) of order 10^{-15} W $Hz^{-1/2}$.

1D and 2D arrays capable of single photon counting in the UV with dynamic range >100 Mcps (million photocounts/second) are needed. Integrated readout and digital signal processing (DSP) electronics with 10-100 MHz frame rates are desired for at least one application, but will be challenging to implement in the decadal timeframe, current capability being in the 1-kHz range.

Integrated detection, amplification, and processing in monolithic or hybrid architectures to improve system robustness are desirable.

<u>Large Aperture Fixed and Deployable Optics</u>

Several direct detection scenarios require deployable collection optics of dimension 3-5m with performance that need not exceed 50x diffraction limited in the UV. This capability is within the current state-of-the-art, however for this size class lightweight structures will become a driving feature. The areal density target is <5 kg m^{-2}.

Lightweighted meter-class collection optics with 1/20-wave surface figure at 2050 nm are required for the coherent detection regime. Active control of the mirror surface is a desirable feature.

Scanning is also required for several of the measurement scenarios. This includes potential full aperture conical or step-stare scanning, or rapid focal plane scanning.

<u>System Alignment Maintenance</u>

Space-based active optical instruments require structures that maintain their shape at micron level spatial scales across the range of temperature experienced in the space environment. This requirement is shared by the passive optical instrument community, which recommends the development of new thermally stable materials suitable for optics and mounts across a temperature range 77-300 K as lightweight alternatives to conventional aluminum-based optical bench structures. Monitoring and maintenance of optical component spatial disposition within the system may significantly reduce risk in certain instrument scenarios by enabling closed-loop active alignment maintenance. This capability would involve the use of laser metrology.

<u>Thermal Control</u>

High pulse energy and high average power (i.e., high PRF) requirements conspire with the invariably low wallplug efficiency (typically <6%) of laser materials to produce large amounts of waste heat that must be dissipated. Some scenarios imply that more than 3kW must be removed from a volume often no more than 2 liters, which is challenging for currently available thermal dissipation mechanisms. Breakthrough approaches in active cooling technologies are needed for many of the measurement scenarios being baselined.

Damage Resistant Optical Materials

High damage threshold (>1 GW cm^{-2}) optics and coatings are needed. Also, narrowband (~1 nm) filters with >95% transmission in visible thru NIR are needed (passbands this narrow are typically achieved with at best 80% transmission).

Table 13 summarizes overall capabilities needed for the active optical remote sensing technologies.

Table 13: Summary of Active Optical Sensor Technology Requirements

Classification	**UV-visible**	**NIR**	**MIR**
Wavelength	350-780 nm	780-1300 nm	1300-11000 nm
Science Application	ozone, land use, land surface topography, ocean productivity, ocean depth sounding, sea ice thickness, tropospheric winds, water vapor, atmospheric temperature, clouds and aerosols	biomass, land surface topography, surface deformation, ice sheet topography, sea ice thickness, water vapor, clouds and aerosols	carbon dioxide, tropospheric winds, ozone, clouds and aerosols
Laser Transmitter	0.5-2.0 J @ 10-100Hz PRF; 200 mJ @ 1-5kHz PRF; 5 mJ @ 10 kHz PRF; 10% wallplug efficiency; 5-year life	0.5-2.0 J @ 10-100Hz PRF; 200 mJ @ 1-5kHz PRF; 5 mJ @ 10 kHz PRF; 10% wallplug efficiency; 5-year life	0.5-5.0 J @100Hz PRF; 200 mJ @ 1-5kHz PRF; 5 -10 W CW; 10% wallplug efficiency; 5-year life
Collection Optics	3-5 m deployable apertures, 50x diffraction limited. <5 kg/m^2 areal density.	3-5 m deployable apertures, 50x diffraction limited. <5 kg/m^2 areal density.	3-5 m deployable apertures, 50x diffraction limited. 1-m rigid apertures with 1/20-wave surface figure at 2050 nm. <5 kg/m^2 areal density.
Receiver Subsystem	detectors: quantum efficiency 30-50%; noise equivalent power 10^-15 W/Hz^1/2; single photon counting in the UV with dynamic range >10^8 photocounts/s in UV; integrated detection, amplification, and processing in monolithic or hybrid architectures	detector quantum efficiency > 80%; integrated detection, amplification, and processing in monolithic or hybrid architectures	detector quantum efficiency > 80%; integrated detection, amplification, and processing in monolithic or hybrid architectures
System Architecture	lightweight and/or composite materials and structures stable at micron-level spatial scales over 77-300 K; thermal dissipation capability of 3 kW from a volume of 2 liters; closed-loop alignment maintenance		

3.1.2 Radar Technologies

Panel B covered technology requirements for active RF (i.e., radar) instruments. The following technology requirements were particularly noteworthy, either because of their wide application to several active RF instrument concepts, or new technology that enables new types of observations. Note that the categories used here are not necessarily mutually exclusive; for example, an instrument record may incorporate both L-band technology and interferometry.

General Issues: Mass and Power Reduction, Enhancing Technologies

In many cases, current active RF technology provides adequate accuracy and performance to satisfy science requirements, but the systems are massive and expensive. Reductions by a factor of 2-3 in power, mass, volume, and cost will enable new missions and allow NASA to fly existing missions more often and with greater coverage, as well as paving the way for their operational use by NOAA and other agencies. Greater reductions will probably be required to enable new airborne and balloon-borne scenarios.

Most active RF instrument concepts would benefit greatly from reducing the mass for large antennas. While "lightweight" can be a relative term, many active RF scenarios require areal densities in the range of 1-10 kg/m2, with < 5 kg/m2 being the most common specification. Several options exist for reducing antenna mass, including deployable mesh, inflatable membranes, and rigid fold-up structures.

Digital beam forming may not be an enabling technology, but it is listed as a highly desirable enhancing technology for many records.

As active RF systems grow in size and capability, they will generate much more data. For this reason, advances in onboard processing, onboard storage, and high-bandwidth communications will become increasingly important for active RF scenarios.

SAR Interferometry

The records in the active RF panel reflect an increasing interest in SAR interferometry (abbreviated InSAR) for Earth science applications. By observing the same scene from slightly different angles, it is possible to create very accurate three-dimensional topographic images through a mathematical process called interferometry. This process requires that both the amplitude and phase information be measured from the radar echo. Applications of this technique include Earth surface topography, sea ice thickness, and ocean surface topography.

Several records in the active RF panel incorporate SAR interferometry, sometimes using coordinated observations from multiple platforms, a single platform operating in repeat-pass mode, or a single platform with two antennas separated by a boom. Clearly, deployable boom technology is significant for single platform InSAR. Booms used in this application range from 10-50 m in length and must be rigid. A significant issue is phase stability for the antennas and receiver electronics, since phase measurement is the foundation of the InSAR technique. Phase stability is specified in the records to be less than 0.01 to 0.05 degrees. Precision metrology for booms and antennas is important for this technology also, since the baseline between the two antennas must be known very accurately. In some cases, new processing algorithms need to be developed to extract the desired measurements from the interferometric data.

<u>UHF (P-band)/VHF Technology</u>

Radars operating in this frequency range are used to measure vegetation biomass and deep soil moisture (1-5 m below the surface). The major UHF and VHF technology challenge is antenna size, but not necessarily light power amplifiers or T/Rs, since arrays are not highly populated and high efficiency amplifiers are already available. Rather, clever beam synthesis techniques with mesh-type apertures may be the best option. Of course, lower mass electronics still are enhancing. Aperture size ranges from 12 x 3-5 m to 30 x 11 m. Areal density should be less than 2 kg/m^2 unpopulated. For UHF and VHF systems, total antenna mass (reflector, feed, booms) should be about 500- 600 kg or less. Mass reduction is cost enabling. Ultra-broadband antennas to accommodate multiple frequencies is an enhancing technology, but will probably not be available in the next ten years.

Another challenge in UHF/VHF technology is the signal processing aspect, since the radar return levels are often lower than at higher frequencies, there is a lot of RFI to remove, and ionospheric effects need to be mitigated. Improved on-board processing and algorithm development would be important for this technology. Downlink data rate is small and should not be a problem.

<u>L-band Technology</u>

Radars operating in the L band are used for measuring freeze-thaw transition, land surface topography, polar ice sheet velocity, snow cover, surface deformation, surface soil moisture, and estimating vegetation characteristics such as height.

L-band technology development needs are mostly in high-power amplifiers and light T/R modules. Transmit power is in the range of 500 to 2000 W with > 60-70% efficiency T/R modules, which should also be radiation hardened (> 2 Mrad), low profile and integrated. Low loss (< 1dB) and high power (> 10W) switches and phase shifters are needed, along with < 50g, 10-30 W high density electronic packaging.

Low frequency radar systems in this panel need rectangular antennas (10-15 x 2-5 m), with areal density <2 kg/m^2. Systems designed for MEO or GEO orbits may need ~10 x 40 m or larger antennas. The antennas may be constructed using either mesh or inflatable/stretch membrane deployable technology. Packaging/attachment technologies on flex would be useful. Metrology for aperture flatness and calibration is a concern, along with thermal management, especially for high-power RF systems. Digital beam forming is a (mostly) enhancing technology: 30 phase-center channels and true time delay capability would be desirable. Ultra-broadband antenna to accommodate multiple frequencies is also an enhancing technology.

Two scenarios refer to MEO and GEO observations, which will require spot beams and radiation shielding (> 10 Mrad).

Data storage of 400 GB may be necessary for some L-band systems.

C-band Technology

Radars operating in the C band are used for measuring sea ice extent and polar ice sheet velocity.

For the scenarios discussed in this waveband, electronically scanned antenna size on the order of 15m x 3m (planar array) is needed. Rigid fold-up or other lightweight technology and structure with areal density less than 6 kg/m^2 are also required. Achieving the science requirements with current technology is feasible now but is too expensive. Mass reduction of the instrument by a factor of 2-3 will be cost enabling.

Ku-band Technology

Ku-band radar systems are used to measure ocean surface winds and ocean surface topography. It will be necessary to reduce the mass, power, and volume of Ku-band systems by a factor of 2-3 in order to transition them to operational weather satellites. Ku-band radars will require either 3 m deployable mesh antennas with aperture efficiency > 80% or 5 m electronic scanning, active phased array antennas with areal density < 5kg/m2. Phase stability requirement is <0.05 degrees with an active Ku-band array antenna. Ku-band systems will also require 50-100 W transmitters (TWTA or SSPA), 500 W TWTA, and 1-2 kW transmitters, depending on the application. Doppler beam sharpening requires advances in calibration techniques for scatterometer applications.

Millimeter-wave Technology (94 GHz)

Millimeter-wave technology is used to measure cloud patterns and internal cloud structure. As in other areas, it is important to reduce mass, power, and cost. Millimeter-wave radars will require special components to operate at this high frequency range, including electronically steered arrays, T/R modules, antenna feeds, high power transmitters, SiG/GaN/InP SSPAs, deployable antennas (>2 m), 10 kW high-power amplifiers at 94 GHz, and low-loss 94-GHz transmission line (< 0.25 dB per foot). Scanning technologies at 94 GHz, including 1 W and 0.25-dB loss T/R modules and low-loss (2-3 dB) phase shifters, have yet to be developed. On-board processing for vertical Doppler, digital beam forming would be useful.

Table 14 summarizes the needed capabilities in this technology area.

Table 14: Summary of Active RF/Microwave Sensor Technology Requirements

Classification	VHF/UHF (P Band)	L Band	C Band	X Band	K, Ku, Ka Band	W & mm Band	SAR	INSAR
Frequency (Wavelength)	0.1-1 GHz (30-300cm)	1-2 GHz (15-30cm)	4-8 GHz (3.75-7.5cm)	8-12 GHz (2.5-3.75cm)	12-40 GHz (7.5mm-1.11cm)	75-300 GHz	Various	Various
Science Application	Deep soil moisture, Biomass, vegetation height, ice thickness	Biomass, growing season length, land cover & use, land surface topography, surface soil moisture, surface deformation, polar ice sheet velocity, snow cover and water equivalent (needs X- or C-band as well)	Sea ice extent, polar ice sheet velocity	Land surface topography, snow water equivalent (needs L-band as well)	Ocean surface winds, ocean surface topography, global precipitation, sea ice thickness and extent, polar ice sheet velocity	Cloud properties & structure	Land & ice surface topography, biomass, vegetation height, polar ice sheet velocity, sea ice thickens, river stage height & discharge, soil moisture	Land surface topography, polar ice sheet velocity, sea ice thickness, river stage height & discharge, snow water equivalent
Antenna type and Size	10-15(m) x 2-5(m) planar array for vegetation; > 30 m x 3-11m for soil moisture, synthesized on mesh reflector with diameter>30m	10-15(m) x 2-5(m) planar array(LEO), 10(m)x40(m) planar array(MEO), > 30 m reflector diameter (GEO)	15(m)x3(m) planar array	1(m)x15(m) planar array	active phase array, reflector > 5 m linear size (LEO), > 10m linear (MEO), >30m (GEO)	active phased array, > 2m linear dimension	See previous columns	See previous columns
Aperture Density (arrays)	< 2 Kg/m^2	< 2 Kg/m^2	< 2 Kg/m^2	< 2 Kg/m^2	< 2 Kg/m^2	< 2 Kg/m^2	< 2 Kg/m^2	< 2 Kg/m^2
Aperture Efficiency	> 80%	> 80%	> 80%	> 80%	> 80%	> 80%	> 80%	> 80%
Boom Size	10-15m for 30-m reflector feed boom	NA	NA	O(50m) for X-band INSAR each side of S/C	NA	NA	10-50 m	10-50 m
Transmit Power	1-2 KW	1-4 KW	1-2 KW	1-5 KW	50W-2kW	1-2 KW	See previous columns	See previous columns
T/R Module Efficiency	> 70 %	> 60 %	> 60 %	> 60 %	> 60 %	TBD		
Phase Stability	< 0.01-0.05 degrees							
Radiation Shielding	>10 Krad LEO; >2Mrad MEO; >10Mrad GEO							
Data Storage	2-10 GB							
Data Rate	10-100 Mb/s	100-300 Mb/s	100-300 Mb/s	300-1000 Mb/s	>1Gb/s	>1Gb/s	See previous columns	See previous columns

3.1.3 Passive Optical Technologies

Panel C covered technology requirements for passive electro-optical sensors. For most records, the panel was able to supply fairly detailed quantitative requirements for technology development. The following list identifies technology needs common to many of the passive electro-optical sensor concepts appearing in the ESTIPS database.

Optical Filters

Optical filters are constructed of materials that allow only light in a certain range of the spectrum to pass through. These filters are used in multispectral detectors. Future Earth science instruments would benefit from improved optical filter coating techniques with a bandpass within 0.2% of center wavelength, in a < f/2 system.

Tunable filters would allow adjustable narrow-band filters without a dispersive penalty. This technology is very difficult but would yield substantial improvements over current filters. Possible approaches include acoustic optical tunable filters (AOTF) and liquid crystal filters.

Optics

Optics for multispectral imaging radiometers are needed that have very low (< 0.5%) polarization over very wide (± 50°) fields of regard. This would solve problems with instrumentally-induced polarization in present instruments.

Wide field (15° - 20°) infrared optics are needed to enable future IR sounders.

Large Aperture Optics

There is a desire to place large aperture (1 m or greater) passive optical instruments in geosynchronous orbit to get high temporal and spatial resolution. An example application is observing marine productivity in coastal regions. Algal blooms can change significantly in a matter of hours, so good temporal resolution is important. Large apertures may also be used to obtain very fine spatial resolution from lower orbits.

Obtaining 100 m resolution from geosynchronous altitude will require beyond state-of-the-art attitude control technology to achieve knowledge: 0.0001 deg, control: 0.01 deg, and stability: 0.00002 deg. Attitude stability is probably the driving requirement for high resolution observations from GEO. Very lightweight high precision mirrors (less than 8 kg/m2) will be needed, along with lightweight structures in general.

Improved Optical Materials For Lenses, Windows, And Beamsplitter Substrates

Materials which will enable lenses, windows, and beamsplitters with the following characteristics are required: available up to 30 cm diameter, easily polished to 0.1 wave, low absorption at wavelengths from 0.4 to > 30 micrometers, not fluorescent after radiation exposure, has either a low index (for windows and beamsplitters) or a high index (for lenses) and low dispersion, not birefringent, strong enough for windows, suitable for cryogenic (77-4K) use, low thermal expansion or compatible with aluminum.

Structures and Materials

Spaceborne instruments require structural materials that maintain their shape and stiffness across a range of temperatures in the space environment. A reasonable goal would be to develop thermally stable (~300K to ~77K) materials for optics and mounts that enable structures lighter than aluminum with similar optical and mechanical performance.

Multispectral Detectors

Multispectral detectors have been used for many years in Earth science applications and there is every reason to expect that they will continue to be useful in the future. Suggested improvements include improved detector gain stability (0.5% over 5 minutes), cross-talk < 0.25 of NESR, and Gaussian noise properties (8x NE @ 3-Sigma), as well as high quantum efficiency (> 70%) and large dynamic range (10^6 to 10^7 electron full well capacity). Several instrument concepts call for thermal IR focal plane arrays that are either uncooled or have modest cooling requirements compared to present technology (e.g., operation at 270K).

Calibration

In order to ensure accurate observations, most electro-optical instruments carry on-board calibration sources. Earth science instruments would benefit from improved calibration sources with 1-5% accuracy and < 1% stability.

Several instrument concepts that were discussed involve replacing whiskbroom scanning with pushbroom scanning. For pushbroom instruments that operate in the thermal IR, new methods of calibration would have to be developed.

Metrology Lasers

On-board metrology lasers are used to accurately measure the alignment of optical components in spaceborne instruments, particularly interferometers. Technology development in this area should focus on long-lifetime, space qualified, stabilized ($d\lambda/\lambda < 5x10^{-8}$), solid state lasers in the visible wavelength range.

Coolers

Detectors in the longer infrared region require cooling to reduce thermal noise and provide adequate signal-to-noise ratio. The panel identified two categories of coolers that would be useful for Earth science instruments: long-lifetime, space-qualified active cryocoolers to 77K requiring a few Watts of power; and passive or low mass, low power active cooler systems to < 120K requiring 1 W or less of power.

Hyperspectral Technology

The hyperspectral approach is now the cutting edge of remote sensing technology. A hyperspectral imager (HSI) can record over 200 spectral channels simultaneously. It is possible to plot hyperspectral data as quasi-continuous narrow bands that approximate a spectral signature. The additional detail greatly enhances the ability to detect and identify materials and objects.

Earth science technology applications of hyperspectral technology include ocean color, land surface vegetation, and land surface composition. The technical requirements for these three applications are sufficiently different to warrant separate instrument scenarios.

Ocean color is an indicator of marine productivity, especially in the coastal regions. Ocean color hyperspectral imagers would operate in the UV/Vis/NIR region. Because biological phenomena such as algal blooms can change dramatically in a matter of hours, high temporal resolution is strongly desired for ocean color observations, leading to geosynchronous platforms.

Land surface vegetation HSI sensors operate in the Vis/NIR/SWIR range and are useful for determining vegetation composition and health. This instrument is distinct from a hyperspectral sensor for ocean color because of differences in dynamic range, polarization requirements, and UV bands.

Land surface composition HSI technology covers the visible and NIR, as well as the MWIR and LWIR range. This type of hyperspectral instrument measures reflected solar and emitted thermal radiation to determine surface composition and chemistry.

Detectors in the 0.3 -2.5 micron range should have the following characteristics: high quantum efficiency (> 70%), large format (2048x2048 pixels), low cost, improved VINIR response < 400nm, improved on detector band pass and order sorting filters, micro lenses for improved MTF (reduced x-talk <1%), higher operating temperatures (80-120 K), and deeper full well > 10^6 electrons to support SNR > 1000.

Detectors in the 3-5 and 8-14 micron range should have: high quantum efficiency (> 70%), large format (2048x2048 for 3-5 microns, 512x512 for 8-14 microns), low cost, improved on detector band pass and order sorting filters, micro lenses for improved MTF (reduced x-talk <2%), higher operating temperatures (80-120 K), deeper full well > 10^6 electrons to support SNR > 500, and improved MWIR and LWIR detectors and yields with better operability 99.9%.

Spectrometers should have better than f/2, low spectral artifacts(<1%), and wide field of view. Optics should have lower scatter < 1%, low polarization < 2%, improved stability < 1% long term (months). New structures should be developed with low cost low CTE materials (SiC) and composites with improved stability, e.g. reduced outgassing and water absorption.

Hyperspectral instruments can easily generate instrument data rates of 1 Gbps. Therefore, hyperspectral instruments in general require advances in data compaction, compression, and high-speed communications. Specifically, these instruments will require high data rate communications > 100 Mbps and data storage > 1 GB.

There are some additional technologies which would greatly enhance hyperspectral sensors. Enhancing electronics technologies include detector chipsets, low power (<500mW) high throughput ASICs (20 MHz - 14 bit), DSP, and low mass electronics (g not kg). HSI would also benefit from cryogenic enabled detector positioning (~ 1 micron) on orbit for focus correction and spectral stability.

Signal to noise ratio was an issue for the EO-1 Hyperion sensor. A trade study to explore combinations of quantum efficiency, aperture, and low noise to achieve desired SNR would be useful.

DSP Studies

The panel consensus was that digital signal processing (DSP) is an important technology for many Earth science instruments. However, the panel lacked the time and resources to establish requirements in this area. Accordingly, the panel recommends studies to establish DSP requirements for all instrument technology records, focusing on questions such as defining "fast" for a given application and quantifying radiation hardness. The study should include both instrument and processing electronics experts.

Sensor Web Studies

The sensor web concept has consistently appeared in Earth science workshops for the past several years. While there still appears to be a fair amount of enthusiasm for this concept, there has been little in the way of specific technology requirements. The lack of requirements may derive from the fact that the sensor web concept requires an integrated system view of technology development. Certain technologies have to be staged together to enable the sensor web. The panel recommends an architecture study to define requirements, especially how to integrate sensors to task each other. Sensor webs need a flexible, responsive operations concept to respond to quickly changing events such as weather. Intelligent agents will be needed to enable automated detection of events. Sensor webs will need true 3D or 4D geographical information systems (GIS) to combine and interpret data. This concept will also require high bandwidth communications using something besides TDRS. An individual spacecraft may or may not have a big downlink requirement; the whole system throughput is the significant factor. UAVs and ground-based sensors should be included in the architecture.

While the sensor web approach is primarily dependent on advances in IT and platform technologies, a sensor web scenario does require different instrument technology developments as well. Large number of spacecraft and instruments require instruments with minimum mass, power, and volume requirements.

Table 15a, 15b, and 15c summarize many of the requirements discussed in this panel.

Table 15a: Summary of Passive Optical Sensor Technology Requirements

Passive Electro-optics: Detectors				
Classification	**Multispectral**	**UV/Vis/NIR Hyperspectral**	**MWIR Hyperspectral**	**LWIR Hyperspectral**
Wavelength	0.3 - 14.5 microns	0.3 - 2.5 microns	3-5 microns	8-14 microns
Size (pixels)	up to 2048x2048	2048x2048	2048x2048	512x512
SNR	> 900	> 1000	> 500	> 500
Quantum Efficiency	> 70%	> 70%	> 70%	> 70%
Cross-Talk	< 0.25 NESR	< 1%	< 2%	< 2%
Full-Well Capacity	1E6 - 1E7	> 1E6	> 1E6	> 1E6
Operating Temperature	270 K	80 - 120 K	80 - 120 K	80 - 120 K

Table 15b: Summary of Passive Optical Sensor Technology Requirements

Passive Electro-optics: Optics and Materials				
Classification	**Filters**	**Optics**	**Large Aperture Optics**	**Optical Materials**
Aperture	NA	NA	1 m	30 cm
Technology Requirements	Filter coatings: bandpass within 0.2% of center in f/2 system. Tunable filters: adjustable narrow band without dispersive penalty (AOTF or liquid crystal).	Polarization < 0.5%. Field of regard +/- 50 deg. IR optics: 15-20 deg field.	Attitude control: knowledge 0.0001 deg, control 0.01 deg, stability 0.00002 deg. Precision mirrors < 8 kg/m2.	Easily polished to 0.1 wave, low absorption 0.4 to > 30 microns, not fluorescent, low dispersion, not birefringent, strong, low thermal expansion, suitable for cryogenic use (4 K), lightweight.

Table 15c: Summary of Passive Optical Sensor Technology Requirements

Passive Electro-optics: Structures, Thermal, Calibration, and Metrology				
Classification	**Structures and Materials**	**Coolers**	**Calibration**	**Metrology**
Temperature Range/Wavelength	77 - 300 K	77 K - 120 K	0.3-14 micron	0.4-0.7 micron
Technology Requirements	Thermally stable, lighter than Al with similar optical and mechanical properties.	Long lifetime, space qualified, 1 W to a few W of power.	Sources with 1-5% accuracy and <1% stability. New methods for pushbroom in thermal IR.	Lasers: long lifetime, space qualified, stabilized (dν/ν < 5E-8, solid state)

3.1.4 Passive Microwave Technologies

Panel D covered requirements for passive RF/microwave technologies. The following list identifies technology needs common to many of the passive microwave sensor concepts appearing in the ESTIPS database.

Synthetic Thinned Aperture Radiometers (STAR)

The STAR technique is a form of imaging radiometry involving a planar array of antenna elements which form a synthetic aperture. The array may be either one dimensional (1D) or two dimensional (2D). Two dimensional arrays may be in either a rectangle or a Y configuration, depending on the application. The complex correlation of the output voltage from pairs of antenna elements is measured at several different baselines formed by the spacing between elements. An inverse Fourier transform is used to construct the image. STAR technology can be used for several applications, including the measurement of ocean salinity, soil moisture, and snow water equivalent.

Low mass (less than 0.2 kg), low power (less than 0.1 - 0.2 W) receiver elements as well as low power (less than 0.1 mW) correlators are needed for this type of radiometer.

STAR radiometers designed to measure soil moisture and ocean salinity operate in the long wavelengths of the L-band, requiring apertures on the order of 20 m. While large aperture technology requirements are dependent on the specific design and application, the following general technology requirements are noted: Deployable structural concepts incorporating tensioned rigid panels or membranes are needed to meet aperture size requirements. Structural components from 6 to 20 m in length are needed for extensible booms and trusses. Such extensible structural elements are characterized by density less than 0.1 kg/m and must be able to support distributed science sensing element mass and data and power cabling which are integrated into structural elements. The structure would be self-sensing and correcting to maintain less than $\lambda/20$ RMS surface distortion requirement. Radiometer stability and accuracy requirement is on the order of 0.1 to 0.4 K over several days.

STAR instruments for measuring snow water equivalent over land would operate in K and Ka-band. Several specific quantitative requirements were established for this STAR application. Metrology/shape control @ $<\lambda/20$ (400 μm at worst, 200 μm desired) is needed. For signal distribution, data rates of 200-400 Mbps over 3 m length are needed. Digital microwave receiver power should be less than 0.1 (2D synthesis) to 0.5 W (1D synthesis) per element. On-board processing requirements include <0.5-mW per correlation with ~10,000 correlators for 1D synthesis; and <0.1-mW per correlation with >1,000,000 correlators for 2D synthesis.

Deployable Mesh Real Aperture Radiometers

An alternative to STAR technology is to use deployable mesh antennas for real aperture passive radiometry. This type of L-band radiometer would also be used to measure soil moisture and ocean salinity. Low loss antenna feeds (less than 1 dB) would be required for this instrument concept. Mesh antennas should have high reflective antenna mesh efficiency (> 0.995). The use of mesh antennas will require new techniques to correct for mesh emission.

High Frequency (mm wave) MMIC Radiometers

Microwave sounders operating in the 50-183 GHz region are used to measure atmospheric temperature, water vapor, and rainfall. These instruments would combine the functionality of AMSU and HSB, and would use MMIC technology to reduce mass, power and cost. Noise equivalent delta temperature (NEDT) of the image would be less than 1 K with an accuracy of 1 K. Noise figure for these radiometers should be less than 4 dB, 10% bandwidth. Required power is less than 0.3 W and antenna beam efficiency greater than 95%.

Submm-Wave Radiometers

This type of radiometers would use new technology to combine submm-wave RF and far IR measurements in one sensor. The instrument would use multi-frequency scattering and absorption by cloud ice particles of microwave emission from moist air below for characterization of ice particle density and size. The key technology development enabling this concept is an advanced 1 THz oscillator, which would allow the combination of sub-mm and far IR measurements. Other technology requirements include improved diagnostics of cloud particle distribution and size; and low mass, low power 100-700 GHz radiometer circuitry. Deployable mm-wave antennas would be needed. A low power spectrometer with 100 channels at 5 GHz bandwidth would be required, along with an arrayed microwave receiver. Highly integrated submm-wavelength signal sources up to 1 THz delivering >1mW of power that can be phase locked to a stable frequency reference would be needed. Low noise (as low as can be achieved) sub-harmonic room temperature mixers would be required also.

Microwave Limb Sounders

The microwave limb sounder concept uses both radiometry and spectrometry in measuring thermal emissions from the atmospheric limb. This technique provides measurements of many atmospheric chemical species, even in the presence of ice clouds and dense volcanic aerosol and smoke. It also measures atmospheric temperature and cloud ice content. Cooled devices provide the sensitivity needed for many tropospheric chemistry measurements. The sensor would operate in five bands between 180 GHz and 2.5 THz.

Enabling technology includes a cryocoolers for ~10 mW heat load at T=4 K, ~200mW at T=~20 K, and ~1 W at T=~60 K, with overall power consumption of ~150 W or less. Requirements also include an antenna system for scanning Earth's limb with ~2 km vertical and ~20 km horizontal resolution at 200 GHz, and reflector surface accuracy of ~10 micrometers. It should be capable of vertically-scanning ~ 1 degree in ~10 s, and azimuth scanning ~ ±75 degrees in ~0.5 s. An overall system design concept will be needed for meeting 0.01 K channel-to-channel measurement accuracy of a ~300 K input thermal signal, and a limited ground or balloon instrument (which can use cryogens for cooling) to determine system-level limitations in tropospheric chemistry measurements.

<u>Other Technology Requirements</u>

A few concepts that were not part of the instrument descriptions were discussed as well. RFI mitigation will become more important. The driving technology for RFI mitigation is digital spectroscopy. RFI technology developed within the telecom industry may be relevant.

Digital beam formed phased arrays are an important topic for both passive and active RF systems. Initial indications are that the sidelobes and overall loss would be significant issues. The concept may have applications for precipitation, allowing the radiometer beam to be steered onto the cell.

The panel discussed a wideband high resolution spectral atmospheric sounder that could scan the entire 50 GHz complex and synthesize sharp weighting functions. An autocorrelator with 7 GHz bandwidth would be needed. This would allow adaptive sounding over the entire range of altitudes. RFI mitigation and wideband high resolution spectral atmospheric sounder in particular are applicable to NPOESS/CMIS

Finally, the panel noted a need for instrument calibration techniques, particularly for, but not limited to, high frequency radiometers with special technology such as spectrometers and SIS.

Table 16 summarizes the overall requirements in this technology area.

Table 16: Summary of Passive RF/ Microwave Sensor Technology Requirements

Radiometers					
Classification	**L Band**	**K, Ka Band**	**High Frequency MMIC**	**Submm-Wave**	**Limb Sounder**
Frequency	1260, 1413 MHz	24.05-24.25 GHz; 33.4-36 GHz	50-55, 170 - 183 GHz	183 - 621 GHz	180 GHz - 2.5 THz
Science Application	Ocean Salinity, Soil Moisture	Snow Water Equivalent	Atmospheric Temperature, Atmospheric Water Vapor, Rainfall from GEO	Cloud Particle Properties and Distribution	Ozone Vertical Profile, Tropospheric Ozone and Precursors, Atmospheric Properties in the Tropopause
Antenna Requirements	Large (12-25 m) rotating deployable antenna designs, e.g. mesh, inflatable. High reflective antenna mesh: >0.995.	REAL APERTURE: Large (>6 m) conical scanning reflector (10-60 rpm). Stowable/deployable. Low microwave emissivity; high-beam efficiency (>90%); at worst 400 microns RMS surface figure. STAR: 2-D structure - stowable/ deployable - (e.g., Y-shaped with >3-m arms, or 6x12 meter cylindrical parabolic reflector fed by 1-D STAR linear feed) supporting >200 microwave receiver elements per arm.	REAL APERTURE: 3-5 m diameter scanning offset parabolic reflector with scanning subreflector. Antenna beam efficiency: >95%. GeoSTAR: Sparsely filled 2-D array of mm-wave receivers, cross-correlated to synthesize the large aperture	1 m (major axis)	Antenna system for scanning Earth's limb with ~2 km vertical and ~20 km horizontal resolution at 200 GHz, and reflector surface accuracy of ~10 microns. Antenna system with ~4x2 m primary reflector, with ~10 micron surface accuracy, stowable within shroud of a modest-size launch vehicle.
Receiver Technology Requirements	Antenna feeds: <1 dB loss. Techniques to correct for mesh emission.	Receiver elements: <0.2 kg, <0.1 W. NEDT <1 K. Correlators <0.1 mW. Signal distribution: 400 Mbps over 3 m. On-board processing: <0.1 mW per correlation with >1,000,000 correlators.	Image NEDT: <1 K. Image accuracy: 1 K. Radiometer noise figure: <3 dB, 10% bandwidth. Radiometer power <0.3 W. STAR will require low power correlators of 0.1 mW per correlation at 200-MHz clock rate.	Low power spectrometer: 100 channels @ 5 GHz BW, I W - arrayed microwave receiver. Highly integrated THz local oscillator sources delivering >1mW.	Cryocooler for ~10 mW heat load at T=4 K; sideband-separating radiometer: 180-280 GHz, >8-20 GHz instantaneous IF coverage, 200-260 GHz tunable LO, and ~100 K or less system noise temperature
Support Structures	Control and stability of large rotating antennae.	Metrology/shape control @ <1/20-wave: 200 microns.	Pointing accuracy to 10% of smallest beam width. Real aperture requires momentum compensated mechanical antenna scanner.	None specified.	None specified.

3.1.5 In Situ, Unconventional, or Non-Spaceborne Technologies

Panel E considered technology requirements for innovative measurement scenarios, including ground-based and in-situ sensors. Measurement scenarios in this panel covered a wide range of options, from terrestrial sensor networks to constellations of GPS receivers. Platform technologies were also examined in this panel; the platform technology results are documented in section 3.2 of this report.

VLBI Technology

The International Very Long Baseline Interferometry (VLBI) Service consists of a terrestrial network of radio astronomy observatories that cooperate to determine polar motion, length of day, and inertial reference by making observations of distant objects such as quasars. Current geophysical measurements are available at the 5 to 20 mm level. Measurement capabilities at the 1 mm level are needed to answer key science questions that have not yet been addressed.

Terrestrial GPS Technology

Military and civilian users have been utilizing signals from Global Positioning System (GPS) satellites to determine position and velocity for several years. GPS signals can also be used to make scientific measurements. Panel E considered both ground-based and space-based uses for GPS receivers.

A closely-spaced terrestrial network of GPS receivers could help estimate earthquake potential, identify active blind thrust faults, and test models of compressional tectonics. It can also be used to measure local variations in strain rate that might reveal the mechanical properties of earthquake faults. In the event of an earthquake, an array of these instruments would measure permanent crustal deformation not detectable by seismographs, as well as the response of major faults to the regional change in strain. This concept could also be used to measure terrestrial reference frame components of position and velocity for a point on the Earth's crust.

The fundamental requirement is less than 5 cm real-time kinematic positioning in all spatial dimensions, with a 1 cm goal. This could be achieved, for example, by the ability to accept real-time corrections from NASA's global differential GPS system together with sufficiently comprehensive in-receiver GPS analysis software. For static positioning, daily precision of less than 0.5 mm in horizontal components and less than 1 mm in vertical components- approximately 5x improvement over current state of the art- is required. To achieve this the receiver may need to be reconfigurable to allow measurement of new GPS III signals, as well as the Russian GLONASS GNSS and/or the European Galileo GNSS. An all-in-view capability may be highly desirable. The receiver/antenna may need to track dual frequency carrier phase down to 5 degree elevation with less than 1 cm multi-path error to help separate the tropospheric parameter from vertical location and clock synchronization parameters.

A robust version of this receiver for rapid deployment (within 24 hours), via ballistic drop from aircraft, for example, is also desirable. Less-stringent positioning requirements -comparable to current state-of-the-art- could be tolerated in this scenario.

GPS Reflection Technology

This sensor option determines ocean surface height by measuring the difference between direct and reflected GPS/GNSS signals. The instrument may also be able to measure ocean surface wind velocity and eddy scale ocean topography from GPS/GNSS reflections.

Capturing ocean surface reflections of the GPS signal requires low-cost, high-precision, steerable, multi-beam antenna systems. Steerable, high-gain (~30 dB), up to 10-beam antennas are required for eddy-monitoring quality topography measurements, i.e. 5 cm accuracy in 25 km x 25 km cell in ten days.

This instrument also requires dual frequency GPS receiver with FPGA architecture to handle a few thousands of correlators with channel synchronization. The receiver should be able to perform closed loop acquisition with cross-correlation outputs every few milliseconds (adjustable). The receiver must also have the ability to process multiple GPS antenna inputs, i.e. at least 2 and preferably 3 or more antenna inputs.

The instrument also has some information technology challenges. The instrument must be capable of processing large data volumes (high-rate GPS data, up to 10 simultaneous reflections and up-looking GPS tracking data) inside the receiver, i.e. on a PowerPC750 or equivalent processor. The system should give operators the ability to upload changes to the flight software operating system and core in-receiver software during flight. Less than 1% amplitude accuracy is required for wind vector measurement.

Enhancing requirements include flying a constellation of satellites to increase measurement accuracy and horizontal resolution; and beam steering via digital base-band processors of the GPS receiver.

GPS-Based Occultation Radiometers

In atmospheric occultation, a signal transmitted by a LEO satellite is received by another satellite, forming a rising or setting pair through the Earth's atmosphere. Atmospheric occultation measurements can provide vertical profiles of water vapor, temperature, pressure and various atmospheric constituents through absorption, depending on the choice of frequency of the transmitted signal.

Atmospheric occultation radiometers would require a scheme to generate tones at about 1 GHz that would be mixed with an intermediate frequency around 10 GHz with a CRO, and up-converted to the final frequency. At this frequency, or at an intermediate one, the tones would be amplified with a solid-state power amplifier to produce 10 mW output per tone, suitable to be radiated by a 30 cm diameter antenna. The main system trade-off is between amplification and antenna size (and hence gain and beamwidth), to achieve voltage signal-to-noise ratio of 1000 or better. The received signals are down-converted to an intermediate frequency near 1 GHz using mixers and frequencies generated by CROs much as in the transmission chain. The received signals are then further down-converted to 0-5 MHz bands which are then sampled and processed by digital processing electronics. (At 10-22 GHz frequencies requirements for tone generation and amplification are met by current technology.)

Atmospheric occultation constellation would also require advances in GPS technology providing global real-time navigation accuracy to 20 cm. The constellation would need long-life GPS receivers for longer duration missions, along with a dual-band L1/L2 GPS flight receiver with 16+ dual-band channels for simultaneous orbit determination and processing of active microwave cross-links. A sub-mm carrier phase on dual- band L1/L2 25-cm pseudorange high-rate data collection for occultations at 20 msec rate would be needed.

Onboard processing of high-rate data inside the GPS flight receiver is required to handle the huge data volume. A PowerPC750 or faster processor inside the GPS receiver would be needed to enable the processing.

Satellite Laser Ranging Network

The Satellite Laser Ranging Network consists of a terrestrial network of ground stations that determine the range to orbiting satellites using lasers. An improved laser ranging network will provide a factor of 5-10 improvement in reference frame and satellite precision orbit determination. Satellite Laser Ranging (SLR) provides center of mass and scale; dual color for atmospheric correction is optimal. Orbiting satellites should be at least to 22,000km altitude to link to GPS satellite constellation. Horizontal spacing should be less than ~5000 km (2000 km optimal). The network should provide global coverage with daily to weekly observation with continuous observations as optimal goal. Precision should be less than 205 mm (1mm optimal).

The improved network would require totally automated and eyesafe operation. The network would need low energy microlasers (130 mJ/pulse) at high repetition rates (2 kHz). The laser beam would fill a 40 cm transmit/receive telescope to meet OSHA radiation standards. No aircraft safety radars would be needed. The lasers would accommodate sub-unity signal-to-noise ratios (SNR) during daylight operations.

Laser Interferometer

The panel investigated laser technology for two spaceborne applications: an interferometer for measuring the Earth's gravitational field and a quantum gravity gradiometer.

The laser interferometer would measure changes in the range between two spacecraft in low-Earth orbits separated by 50-200 kilometers to detect perturbations caused by the

Earth's gravity field, along with a force reduction system on each spacecraft to reduce non-gravitational forces. The instrument is distributed, with each spacecraft containing identical transmit/receive optical systems, frequency-stabilized lasers, measurement electronics, and force reduction systems.

The primary instrument performance requirements are continuous measurement of change in range between spacecraft separated by 50-100 kilometers with accuracy of 0.1 nanometers rms over 100 second averaging times, combined with reduction of accelerations due to non-gravitational forces to less than 10^{-15} m/s^2 rms over 100 seconds. Subsystem component requirements include: single-mode laser with power 10-30 mW, natural frequency noise <100 MHz over 100 second sampling time; laser frequency stabilization system with stability of 10^{-15} rms over 100 seconds; laser frequency measurement system with accuracy $<10^{-5}$Hz rms for averaging times of 100 seconds, over dynamic range of ~5 MHz; Gravitational Reference Sensor with a test mass isolated to less than 10^{-15} m/s^2 rms over 100 seconds and a measurement system for providing a measure of the spacecraft position with respect to the test mass with accuracy of 1 nanometer rms over 100 seconds; and a Micro-Thruster system to adjust the spacecraft position to stay centered on the test mass to within 1 nanometer rms over 100 seconds, with thruster requirement of 2-100 micro-Newton with step size 0.1 micro-Newton and noise less than 0.01 micro-Newton rms over 100 seconds.)

<u>Quantum Gravity Gradiometer</u>

A quantum gravity gradiometer measures the gravity tensor using matter-wave interferometry. The instrument consist of two accelerometers separated by a distance. Each accelerometer is based on an atomic fountain and matter wave interferometry. The fountain consists of cold atoms that are produced in a magneto-optical trap by laser cooling, and are then launched out of the trap. The associated De Broglie waves of the cold atoms are divided into two paths by laser light. Gravity, acting on the moving atoms, distorts the phase of the matter waves and changes the interference pattern, which can be detected using laser resonance fluorescence technique.

The quantum gravity gradiometer is a completely new instrument concept. Technology requirements include compact and robust laser systems and a compact cold atom beam source. Compact (less than 1000 cm^3) laser sources should be capable of providing at least 1 W of intensity, with line width less than 500 kHz, at wavelengths corresponding to cesium and rubidium atom transitions. Beam shaping, and beam delivery systems should be compact (less than 1000 cm^3). Compact (less than 0.25 liter) source of high flux (more than 10^{10}/s) atoms should have transverse temperature less than 3 micro-Kelvin. Gravity gradiometer should provide 1-axis measurements with accuracy less than $\sim 10^{-15}$ m/s/s/m rms over averaging times of 1 to 1000 seconds. Instrument lifetime should be at least 12 months (5 years preferred). Related instrument requirements include small (less than 5x5x7 cm) vacuum pumps capable of sustaining ultra-high vacuum (less than 10^{-10}) Torr for a volume of about 5 liters. High performance isolation system will be needed to provide 30 dB of vibration isolation for a mirror with a mass of 50 gm, across the frequency band of 10 to 1000 kHz.

Surface Rover

In this scenario, a long-range surface rover would be used to determine sea ice thickness and snow cover by electromagnetic induction and acoustics. The data would support spaceborne passive microwave and radar sea ice observations.

The rover must be lightweight, autonomous, solar or wind-powered, weather survivable, and capable of detecting and traversing open water, thin ice, rough ice and ice ridges. The vehicle must possess a satellite communications system. The rover must have the capability to autonomously perform transect of Arctic Ocean sea ice for distances of at least 1000 km, monitor location within 1 km horizontally and 10 cm vertically, and communicate results and location back to the continent.

The electromagnetic induction sensor operates in VHF and determines local conductivity, which is inverted to develop ice thickness. Electromagnetic induction is routinely used for sea ice thickness determination from helicopters and surface vehicles. The sensor will acquire ice thickness data of 5 cm or 2% (whichever is larger) accuracy. The acoustic sensor operates at the tens of kHz range and measures snow thickness on the ice. An acoustic device for snow has not been developed.

Balloon-Based Observations

The panel identified two balloon-based observations: one for measuring the Earth's magnetic field and the other for measuring atmospheric temperature, water vapor, ozone, and winds.

Both scenarios rely on new balloon technology. Long-duration, high strength-to-weight ratio balloon film materials would be required, along with an automated dropsonde storage and deployment system. A balloon trajectory control system (TCS) for constellation control, adaptive observations, and coordinated satellite measurement would be needed. These scenarios require trajectory control to 1 to 2 m/sec in conjunction with a constellation of balloons. To meet constellation control requirements 2 m/s may be required (assuming a 10 m/s relative wind between 20-and 35 km). Winds of 20 to 30 m/sec can occur at this altitude, but with enough balloons the constellation can achieve required coverage.

Measuring the magnetic field will require multiple stratospheric long-duration balloons with trajectory control capabilities at 30-35 km altitude supporting an array of vertically separated magnetometers on a long (several km) tether. Magnetometer mass must be less than 5 kg compared with 10 kg currently available. Low power (< 5 W) vector measurement package with nano-tesla sensitivity will be required.

The second balloon scenario would measure atmospheric temperature, water vapor, ozone, and winds from stratosphere (35 km) to surface using a meteorological dropsonde deployed from a long-duration stratospheric platform. This sensor option would be an advanced NCAR GPS dropsonde type with the added ozone sensor and water vapor sensor that can meet 1% accuracy at greater than 20 km. The atmospheric winds would be recovered via GPS tracking.

Current dropsondes do not measure ozone and have a mass of about 400 to 500 g. Mass reduction to below 100 g would allow for thousands of dropsondes on a single platform. This will require considerable sensor technology development. Lower mass would reduce the probability of damage to aircraft or people and property on the ground, thereby increasing the probability of getting clearance to drop. Operation of a water vapor sensor above 20 km altitude at 1% accuracy is considered a significant technology challenge. Individual dropsonde battery storage life of one year will be required.

3.2 Platform Technologies

Panels A, B, C, D, and E reviewed a set of new platform technologies that would benefit a wide range of scenarios. Requirements were quantified for many of the technologies, but a few would require additional follow-up with experts, and those few currently lack detailed quantification. Many of the new technologies could reach TRL 6 within the next 5 to 10 years. Some technologies are currently at TRL 2 or 3, and further effort is needed before the technology matures enough to estimate availability dates.

Many of the proposed platform technologies are enhancing, and a few are enabling. A recurring theme for enhancing technologies is that of reduced mass, power, and cost while providing performance comparable to or better than currently available technologies. One rationale for proposing enhancing technologies is that reduced mass, power, and cost for platforms would mean increased mass, power, and dollars available for instruments, potentially leading to greater science return. In addition, a significant reduction in platform cost could make enough difference for a scenario to come in under its cost cap. In that sense, some enhancing platform technologies could be considered cost enabling.

A few platform technologies can be considered enabling for scenarios that require much greater capability than can currently be achieved. Optical communications could be enabling, for instance, for a scenario that requires higher data rates than can be achieved with RF communications. The additional cost for enabling platform technologies would raise the overall cost, but could make a scenario feasible where it would not have been otherwise. In that sense, the value of enabling platform technologies is tied directly to the value of the science in some of the more challenging scenarios.

Platform technologies in the ESTIPS database can be categorized as indicated below. There were one or more general themes within each category, which are described in the following.

3.2.1 Command & Data Handling (C& DH)

Many commercially available C & DH components are not currently rad hard to the extent that might be needed to support a variety of long duration scenarios in orbits for which the radiation dose is significant. One main theme for C & DH was the need for rad-tolerant digital signal processing, analog circuitry, FPGA's, and ASIC's. These new technologies would be enhancing for a wide variety of scenarios due in part to significantly reduced mass. The current approach is to use available components and add heavy shielding when required to survive a high total radiation dose.

Quite a few scenarios require collection, storage, and transmission of large volumes of science data. Storing science data volumes may require data storage density > 100 Gb/cm^3. Candidate technologies for high-density data storage include micro-electro-mechanical systems (MEMS), magnetic, optical, and hybrid magnetic/optical.

Table 17 summarizes the requirements in this area.

3.2.2 Communications

A major theme for Communications is the ability to support higher data rates needed to downlink large science data volumes. An optical communications system is an enabling technology for a mission requiring > 1.2 Gbps downlinks. Links of equal or lesser rates can be achieved with RF systems using existing technology for lower cost. For an optical system data rates >> 10 Gbps may be achievable, possibly up to 30 Gbps.

Transformational RF products could lead to development of key technologies in broadband radar, sensing, and communications to improve the data rate, functionalities and efficiencies of today's RF capabilities. A key area includes the following: high-power, high-efficiency transmitting systems which utilize advanced wideband phased array antennas for telecomm and radar applications; advanced solid-state amplifier materials including wide bandgap semiconductors such as gallium nitride (GaN) and antimonide (GaSb) technologies; and other semiconductors, i.e., InP MHEMT's for T/R-module based arrays and as embedded active amplifier elements for stowable arrays.

Transformational RF comm based on enabling transmitting technologies will increase the nominal data rates to > 100MBPS thus occupying a place in high data rate communications as a standalone system or a relay platform for other RF or optical systems. Bandwidth efficient modulations based on optical modulating architectures for arrays will simplify complexity of arrays in advanced phase-shifter less applications. At Ka-band, the potential to employ retro-directive steering and multiple tracking enables programmable scenarios for constellation communications and science.

Table 18 summarizes the requirements in this area.

3.2.3 Guidance Navigation & Control (GN & C)

For the most part, GN&C platform technologies have to do with sensors used to measure platform attitude, rate, position, and velocity. A general theme in this category was one of significantly reduced mass and power and reduced cost as a result of new fabrication techniques related to miniaturization. For instance, rate sensing gyros can be manufactured using micro-electro-mechanical systems (MEMS) technology, so that a set of 3 gyros could potentially be packaged in an IMU with a mass < 400 grams that requires from < 1 Watt and costs < $5 K. For comparison, one of today's smallest space-qualified IMU's has a mass of 0.75 kg, requires 12 Watts, and costs > $110 K. MEMS gyros provide an example of an enhancing technology that could benefit a wide variety of scenarios.

Table 19 summarizes the requirements in this area.

3.2.4 Material & Structures

There is a need for large structural platforms for RF and optical sensors. Some scenarios require one-dimensional booms ranging in length from 10m to 50m and having interferometric stability. Other scenarios require two-dimensional platforms (e.g., 3m by 50m or 20m by 20m) for synthetic and filled radar/RF systems with surface accuracies to less than 0.1 mm RMS. All platforms must have sufficient packaging density and low enough mass to fit in moderate size launch vehicles.

Some of these large structures would be an order of magnitude larger than can be achieved using current technology. So, a major theme for Material & Structures is the ability to deploy lightweight, large space structures with low packing volume. One approach would involve inflatable, self-rigidizing booms used to support mesh antennas. Techniques have also been proposed for in-space construction of large structures based on polymers. One such approach would involve thermal curing using resistive heating.

Table 20 summarizes the requirements in this area.

3.2.5 Power

The themes for new power technologies are increased efficiency and lifetime, and reduced mass. For instance, Lithium Ion batteries could potentially store 2 to 6 times more power than equally massive Nickel-Hydrogen batteries. Lithium Ion batteries need to be space-qualified and have a lifetime 3 to 5 years of operation in LEO to support Earth science.

Current solar cells have efficiencies < 30%. By adjusting the band-gap for two materials for an optimal overlap, it might be possible to achieve solar cell efficiency in the range of 50 to 70%. This kind of technological advance could revolutionize power generation for space platforms.

Table 21 summarizes the requirements in this area.

3.2.6 Propulsion

A number of propulsion technologies fall within the general category of "Advanced Propulsion Management" technologies that includes ultra-lightweight fill and drain valves, tanks, filters, isolation valves, pressure regulators, pressure transducers, etc. Advanced Propulsion Management is focused on developing a variety of ultra-lightweight propulsion subsystem components to reduce overall spacecraft mass.

Several propulsion technologies fall within the general category of "Advanced Electric Propulsion." In this category, acceleration will be achieved electro-thermally, electro-statically or electro-magnetically. In electro-thermal thrusters, the propellant is electrically heated and expanded through a nozzle. Examples include resistojets and arcjets. In electro-static thrusters, propellant is ionized and the resulting ions are accelerated through an electric potential. Examples include the Hall effect thruster, the ion engine, and the colloidal thruster. Electro-Magnetic thrusters utilize electric and magnetic forces to accelerate ions. An example of this is the Magneto-Plasma-Dynamic thruster. Advanced Electric Propulsion is focused on developing a variety of very efficient, low thrust, low noise, high specific impulse electric thrusters to meet challenging attitude and orbit control requirement in an affordable manner with lower mass and power.

Table 22 summarizes the requirements in this area.

3.2.7 Thermal

For high-energy instruments, there can be a need for active heat management. For instance, a high-powered laser that generates large amounts of waste heat could need a heat pump to help manage its heat load. Heat pumps currently used for ground applications tend to be heavy, and none have been space qualified yet. Consequently, a major theme for Thermal has to do with new technologies for transporting and dissipating large heat loads over long (e.g., 10 to 15 year) lifetimes. This includes several types of heat pumps as well as spray cooling, new high conductivity materials, and high flux heat exchangers.

Components on platforms are typically designed to operate near room temperature. On the other hand, some instruments may require low temperature operations (e.g., IR imager with a cool focal plane). Most thermal energy transport technology is designed for room temperature operations. So, new technology is needed to support instrument operations down to -100 degrees C. One such technology would be an alternate working fluid for low temperature operations.

Particularly for thermal control of small (e.g., micro) satellites, there is a need to provide thermal control with mass $< 1\ kg/m^2$ and emissivity tunable over a range from 0.1 to 0.8. Photochromic or electrochromic materials could provide the means to do this. These would have > 200 times less mass than that required for current louvers.

Table 23 summarizes the requirements in this area.

Table 17: Summary of Command and Data Handling Requirements

Command & Data Handling				
Platform Technology Requirement	**Science Application(s)**	**Performance Goals**	**Mass Goal**	**Radiation Goals**
Provide design and fabrication techniques for radiation tolerant system-on-a-chip.	In the near term, especially useful for Active Optical science on Airborne platforms. As the technology matures, generally useful for all types of science on small (e.g., micro) satellites, and especially useful in high radiation environments.	Goal of achieving integrated avionics subsystem on a single chip. Would include functions for many subsystems and could result in large mass savings.	< 200 grams	Capable of surviving a minimum total dose > 10 krad with a radiation dose margin (RDM) of 1. Full goal would be capability to survive > 1 Mrad total dose with an RDM of 1. In addition to total dose radiation, radiation requirements for Single Event Upset (SEU) of approximately LET greater than 75MeV-cm2/mg, and Single Event Latchup (SEL) immune.
Data storage density > 100 Gb/cm^3, data transfer rates > 1 Gb/sec to support scenarios with large science data volumes.	General applicability and especially useful for Active and Passive Optical and Active RF science on Space Borne and Airborne platforms.	Data storage density > 100 Gb/cm^3, data transfer rates > 1 Gb/sec.		
Rad-hard digital signal processors capable of surviving a total dose > 1 Mrad.	Applicable in high radiation environments and especially useful for Active and Passive RF, and Passive Optical science on Space Borne platforms.	Rad-hard digital signal processors capable of surviving a total dose > 1 Mrad.		Capable of surviving a total dose > 1 Mrad with a radiation dose margin (RDM) of 1. In addition to total dose radiation, radiation requirements for Single Event Upset (SEU) of approximately LET greater than 75MeV-cm2/mg, and Single Event Latchup (SEL) immune.
COTS FPGA with shielding, packaging, system architecture, and EDAC software for radiation hardness.	Applicable in high radiation environments and especially useful for Active and Passive RF, and Passive Optical science on Space Borne platforms.	Projected 5-year reliability and availability >= 0.99999 at probability 0.99999 Reliable continued operation in presence of SEU induced faults must be obtainable either by the inherent FPGA technology or by user implementation. Additional goal of built-in (completely contained within the device) self-test and self-repair capability that would automatically reassign functionality of damaged cell to another cell.		System tolerance SEL immune. System tolerance TID >= 1 Mrad with a radiation dose margin (RDM) of 1.
ASIC libraries for Earth science on-board digital processing applications with shielding, packaging, system architecture, and EDAC software for radiation hardness.	Applicable in high radiation environments and especially useful for Active and Passive RF, and Passive Optical science on Space Borne platforms.	ASICs would use standard industry design, materials, and foundry processes. Projected 5-year reliability and availability >= 0.99999 at probability 0.99999 Reliable continued operation in presence of SEU induced faults.		System tolerance SEL immune. System tolerance TID >= 1 Mrad with a radiation dose margin (RDM) of 1.
Rad-tolerant analog circuitry and mixed-signal ASIC libraries to reduce mass, power, and cost.	General applicability and especially useful for Active and Passive RF, and Passive Optical science on Space Borne platforms.	Rad-tolerant analog circuitry and mixed-signal ASIC libraries to reduce mass, power, and cost. Libraries would help to avoid repeated custom design that raises cost.		Minimum goal would be capability to survive a total dose > 10 krad with a radiation dose margin (RDM) of 1. Full goal would be capability to survive a total dose > 1 Mrad with an RDM of 1. In addition to total dose radiation, radiation requirements for Single Event Upset (SEU) of approximately LET greater than 75MeV-cm2/mg, and Single Event Latchup (SEL) immune.

Table 18: Summary of Communication Requirements

Communication						
Platform Technology Requirement	**Science Application(s)**	**Performance Goal(s)**	**Mass Goal**	**Input Power Goal**	**Output Power Goal(s)**	**Volume Goal**
Relay data at very high rates for downlink to Earth to support scenarios with large science data volumes.	Especially useful for Active RF and Passive Optical science on Space Borne platforms.	For an optical system, data rates >> 10 Gbps may be achievable, possibly up to 30 Gbps. Goal of laser-communication terminals capable of locking to each other when in LEO-GEO orbits, to support at least 10 Gbps communication link.	For an optical system, total mass < 30 kg	For an optical system, total power < 100 W		
Higher data rate RF communications for data pipe links to Earth or other constellation spacecraft, continuous or periodic, radar or CW.	Especially useful for Active and Passive Optical, and Active RF science on Space Borne and Airborne platforms.	High-performance solid state phased array antenna to allow electronic beam steering, multi-carrier communications and tracking, dual pulse-multi frequency radars. Reduced complexity electronically steerable phased arrays for lower overall cost. Using Gallium Nitride semiconductor material for RF devices could lead to output power densities a factor of 6 or more higher than achievable with existing semiconductor materials in applications from 1 GHz up to 40 GHz. Goal using Gallium Nitride wide bandgap type semiconductor of >25% PAE at S, X or Ka-bands.			>100W with direct bus voltage EPC's. Individual devices or MMICs will support goals of 5-10W and higher and arrays will support >100W through Ka-band.	
Low power, low volume telecom hardware.	Especially useful for Active RF science on Airborne and Lighter than Air platforms.			< 8 Watts		< 1000 cm^3

Table 19: Summary of Guidance, Navigation, and Control Requirements

GN&C					
Platform Technology Requirement	**Science Application(s)**	**Performance Goals**	**Mass Goal**	**Power Goal**	**Recurring Cost Goal**
Low mass, low power, low cost integrated avionics sensor suite.	General applicability and especially useful for Active RF and Passive Optical science on the following platforms: Airborne, Lighter than Air, and constellation of small satellites.	Min goals: 3-sigma per-axis knowledge to within + - 0.1 deg, 1-sigma gyro bias stability < + - 0.5 deg/hr, 1-sigma ARW < + - 0.25 deg/rt-hr, 1-sigma per-axis accelerometer bias < 100 micro-g, update rate of 2 Hz Full goals: knowledge to within + - 30 arcsec, gyro bias stability < + - 0.1 deg/hr, ARW < + - 0.05 deg/rt-hr, accelerometer bias < 10 micro-g, update rate of 10 Hz	Min goal: < 1.5 kg Full goal: < 1 kg	Min goal: < 2.25 W Full goal: < 1.5 W	Min goal: < $400 K Full goal: < $250 K
Low mass, low power, high accuracy attitude determination sensor.	General applicability and especially useful for In-Situ and GPS science on the following platforms: Lighter than Air and constellation of small satellites.	3-sigma per-axis accuracy in the range of + - 3 to + - 6 arcsec.	< 100 grams (not including electronics)	< 100 mW (not including electronics)	
Low mass, low power, high accuracy, low cost gyros.	General applicability and especially useful for Active Optical, Active RF, Passive Optical, In-Situ, and GPS science on the following platforms: Airborne, Lighter than Air, and constellation of small satellites.	1-sigma per-axis bias stability < 0.01 deg/hr, 1 ppm SF variation, 1-sigma per-axis ARW < 0.001 deg/rt-hr, 1 to 2 cubic inches volume.	200 to 400 grams for 3 gyros packaged in an IMU	0.5 to 1 Watt	< $5 K per unit
Low mass, ultra-high accuracy accelerometers.	Applies specifically to measurements of the geopotential reference surface and the Earth gravity field using laser interferometry between two spacecraft in low Earth orbit.	Resolution < 1 nano-g.	< 100 grams		
Highly accurate real-time knowledge of relative position for satellites in close proximity (e.g., within kilometers).	Especially useful for Active RF on an Airborne platform.	Real-time knowledge of relative position for satellites in close proximity (e.g., within kilometers) accurate to within a 3-sigma error radius of milli-meters.			
Low mass, low power, low cost GPS receivers.	General applicability and especially useful for Active Optical, Passive Optical, and In-Situ science on the following platforms: Airborne, Lighter than Air.	Required real-time performance would be an error radius within 10 meters, 1 sigma.	< 0.5 kg	< 2 Watts	$25K to $75K
Trajectory control to support precision or targeted payload recovery for balloon scenarios.	Specifically for Active RF, Passive Optical, and In-Situ science on Lighter than Air platforms.	Near term goals of control authority around 1 meter/sec over a 100 day lifetime. Far term goals of control authority to 2 to 5 meters/sec over a 3 to 5 year lifetime.			
Ultra-precise real-time absolute and differential position.	Especially useful for Active Optical, Active RF, and GPS science on Space Borne and Airborne platforms.	Real-time absolute position < 1-cm radial component; < 1-mm differential position (between similarly-equipped platforms separated by < 200 km); < 5 picosecond differential timing; on-orbit life > 5 yr; number of satellites tracked: all in view up to 36 (multiple GNSSs, up to 9 observables per transmitting satellite); post-launch reconfigurability. Configured to receive differential GPS corrections from NASA's global differential system.	< 5 kg (including antenna)	power < 20 W	

Table 20: Summary of Material and Structure Requirments

Material & Structure				
Platform Technology Requirement	**Science Application(s)**	**Performance Goal(s)**	**Mass Goal(s)**	**Design Life Goal**
Lightweight, large space structures with low packing volume.	Especially useful for Active and Passive RF, and Passive Optical science on Space Borne platforms.	Space-deployable booms that meet the following requirements: Length: up to 20 meters Axial buckling capability greater than 450 N (with simply-supported end conditions) Packaging factor (as defined by the ratio of deployed volume over packaged volume) greater than 20 Thermally stable (with a near-zero CTE in the operating temperature range) Single- and multiple-layer membrane apertures that meet the following requirements: Aperture area larger than 900 square meters (30 M x 30 M) Packaging efficiency (as defined by inherent material volume/packaging container volume x 100%) greater than 15% Space deployable (by deployment of the support structures)	Booms with mass less than 0.2 kgs/linear meter (including endcaps and deployment control) Single- and multiple-layer membrane apertures with mass density less than 0.18 kgs per square meter (system mass that includes support structures, inflation system, launch restraints and release mechanisms, but excludes electronics and RF components)	Greater than 10 years
Integral data interconnects in inflatable/deployable structures to support large antennas.	Especially useful for Active and Passive RF science on Space Borne platforms.			

Table 21: Summary of Power Requirements

Power			
Platform Technology Requirement	**Science Application(s)**	**Performance Goal(s)**	**Design Life Goal**
Advanced solar cells with efficiency greater than 40%.	Useful in general for Active and Passive Optical, Active and Passive RF, GPS, and In-Situ science on Space Borne, Airborne, Lighter than Air, and Surface platforms.	Efficiency greater than 40%.	
Thin-film solar cells on flexible substrate.	Especially useful for Active RF, Passive Optical, and In-Situ science on Lighter than Air platforms.	> 20% conversion efficiency (with unconcentrated light)	> 5 years in a space environment
High energy density, space-qualified batteries.	Particularly applicable when mass is limited and especially useful for Active and Passive Optical, and Active and Passive RF science on Space Borne, Airborne, and Lighter than Air platforms.	Specific energy 200 Wh/kg.	15,000 to 25,000 cycles (3 to 5 years of operation in LEO)
Complete flywheel energy storage system.	Especially useful for Active Optical science on Space Borne platforms.	Density of 300 W/kg, 85- 95% round-trip efficiency.	7 years

Table 22: Summary of Propulsion Requirements

Propulsion						
Platform Technology Requirement	**Science Application(s)**	**Performance Goal(s)**	**Mass Goal(s)**	**Thrust Level Goal(s)**	**ISP Goal(s)**	**Minimum Impulse Goal(s)**
Small, low mass, Low thrust, high ISP thrusters to support small (e.g., micro) satellites.	Useful in general for all types of science on small (e.g., micro) Space Borne platforms.	Affordable micro-electro-mechanical systems (MEMS) thrusters that utilize either chemical, electrical or cold gas technologies.		10-500 milli-N	150-300 seconds	
Low thrust using cold gas to minimize contamination of cold optics.	Especially useful for Passive Optical science on Space Borne platforms.	Thruster lifetime 5-10 years	thruster mass < 1 kg	10 to 40 milli-N	150 - 300 seconds	
Very low minimum impulse thrusters for use in achieving precision pointing control without reaction wheels.	Useful in general for all types of science on Space Borne platforms.	Thrusters that utilize either chemical, electrical or cold gas technologies.		0.7-N		< 1 to 3 milli-Ns
Low mass, low thrust, low noise, high ISP advanced electric propulsion.	Especially useful for In-Situ science that requires laser interferometry between two spacecraft in Earth orbit.	Overall efficiency 25% - 40% Thruster lifetime 5-10 years	thruster mass < 1 kg to 3 kg	1 micro-N to 10 milli-N	300 to 13000 seconds	as low as 30 to 50 μN-sec
Ultra-lightweight propulsion subsystem components to reduce spacecraft mass.	Particularly applicable when mass is limited, and especially useful for GPS science using a constellation of small (e.g., micro) satellites.	See mass goals.	3 kg for tank capable of holding 20 kg 5 to 55 grams for a pressure transducer < 100 grams for a filter < 10 grams for a fill and drain valve			

Table 23: Summary of Thermal Requirements

Thermal				
Platform Technology Requirement	**Science Application(s)**	**Performance Goal(s)**	**Mass Goal**	**Design Life Goal(s)**
Thermal control for small (e.g., micro) satellites.	Particularly applicable when mass is limited and especially useful for GPS science on Space Borne constellations of small satellites.	Emissivity tunable over a range from 0.1 to 0.8	< 1 kg per square meter	
Thermal paint that is stable in a LEO or GEO orbit while exposed to 1 AU solar intensity and radiation environment.	Especially useful for Passive Optical science on Space Borne platforms.	Stable thermal paint with absorptivity < 0.2 at beginning of life.		Absorptivity that changes by < 15% over 5 to 10 years in a LEO or GEO orbit while exposed to 1 AU solar intensity and radiation environment.
Thermal energy transport technology to support low-temperature instrument operations.	Applicable when low-temperature instruments are needed for science and especially useful for Passive Optical science on Space Borne platforms.	Support instrument operations down to -100 degrees C.		
Precision thermal control for precision instruments that are highly sensitive to thermal variations (e.g., precision optics).	Especially useful for Passive Optical science on Space Borne platforms.	Precision thermal control to within + - 0.1 degree or better		
Precision temperature sensing for instruments that are highly sensitive to thermal variations (e.g., precision optics).	Especially useful for Passive Optical science on Space Borne platforms.	Precision temperature sensing to within + - 0.01 degrees or better		
Long life pumps for thermal energy transport to support high-energy instruments.	Applicable when high-energy instruments are needed for science and especially useful for Active Optical science on Space Borne platforms.	Space-qualified pumps with higher efficiency and reduced mass compared with current technology.		10-15 years continuous operation
New spray cooling systems for dissipating large heat loads.	Applicable when high-energy instruments are needed for science and especially useful for Active Optical science on Space Borne platforms.			
New high conductivity materials to dissipate large heat loads.	Applicable when high-energy instruments are needed for science and especially useful for Active Optical science on Space Borne platforms.			
High flux heat exchangers to dissipate large heat loads.	Applicable when high-energy instruments are needed for science and especially useful for Active Optical science on Space Borne platforms.			

Appendix A: Workshop Structure

Workshop Chair
Azita Valinia (NASA/ESTO)

Panel A
Facilitator: Dave Tratt (NASA/ESTO)
Co-Chair: Bruce Gentry (NASA/GSFC)
Co-Chair: Gary Spiers (NASA/JPL)
Executive Panel Members:
Farzin Amzajerdian (NASA/LaRC)
Arlyn Andrews (NASA/GSFC)
Randy Bartman (NASA/JPL)
Bill Heaps (NASA/GSFC)
Syed Ismail (NASA/LaRC)
Mike Krainak (NASA/GSFC)
Frank Peri (NASA/LaRC)

Panel B
Facilitator: Tom Cwik (NASA/ESTO)
Co-Chair: Gerry Heymsfield (NASA/GSFC)
Co-Chair: Mahta Moghaddam (NASA/JPL)
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Wendy Edelstein (NASA/JPL)
Dan Evans (Aerospace)
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Mike Lou (NASA/JPL)
Soren Madsen (NASA/JPL)
Rafael Rincon (NASA/GSFC)
Paul Siqueira (NASA/JPL)
Simon Yueh (NASA/JPL)

Panel C
Facilitator: Loren Lemmerman (NASA/JPL)
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Co-Chair: Jim Gleason (NASA/GSFC)
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Dave Content (NASA/GSFC)
Dave Glackin (Aerospace)
Scott Janz (NASA/GSFC)
Dave Johnson (NASA/LaRC)

Zakos Mouroulis (NASA/JPL)
Jon Neff (Aerospace)

Panel D
Facilitator: Bob Menzies (NASA/JPL)
Co-Chair: Terry Doiron (NASA/GSFC)
Co-Chair: Bjorn Lambrigtsen (NASA/JPL)
Executive Panel Members:
Bob Bauer (NASA/ESTO)
Dave Kunkee (Aerospace)
Wes Lawrence (NASA/LaRC)
Jeff Piepmeier (NASA/GSFC)
Jim Shuie (NASA/GSFC)
Joe Waters (NASA/JPL)
Bill Wilson (NASA/JPL)

Panel E
Facilitator: Robert Ferraro (NASA/JPL)
Co-Chair: Peter Hildebrand (NASA/GSFC)
Co-Chair: Jim Zumberge (NASA/JPL)
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Ernie Robinson (Aerospace)
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